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Technology Needs for High Speed Rotorcraft (3)

Jack DeTore and Scott Conway

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National Aeronautics and
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Technology Needs for High Speed Rotorcraft (3)

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October 1991

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Space Administration

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SYMBOLS AND ABBREVIATIONS

2-D	two-dimensional
AGL	above ground level
APU	auxiliary power unit
ART	Advanced Rotorcraft Transmission
BHTI	Bell Helicopter Textron, Inc.
C	degrees Celsius
C_D	drag coefficient
C_L	lift coefficient
C_T	rotor thrust coefficient
CTOL	conventional takeoff/landing
CTR	Civil Tilt Rotor
DOC	direct operating cost, U.S. dollars
dBA	deciBel, A-scale
deg	degree, degrees
DGW	design gross weight, pounds
E	modulus of elasticity
f	allowable stress
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
f_e	equivalent flat plate drag area, ft^2
fps	feet per second
ft	foot, feet
g	acceleration due to gravity
G	shear modulus
GARP	General Advanced Rotorcraft Program
GW	gross weight, pounds
HI-STEP	High-Speed Total Envelope Proprotor
HOGE	hover out of ground effect
hp	horsepower
hr	hour, hours
HSRC	High Speed Rotor Craft
ICAO	International Committee Civil Aviation Organization
IHPTET	Integrated High Performance Turbine Engine Technology
IR&D	independent research and development
ISA	International Standard Atmosphere
K ft	1000-feet
ktas	knots true airspeed
lb	pound, pounds
M_{dd}	drag divergence Mach number, n.d.
MTBF	mean time between failure
MTTR	mean time to repair
N_2	engine power turbine shaft speed, rpm
N.A.	not applicable

SYMBOLS AND ABBREVIATIONS (CONCLUDED)

NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NFAC	National Full-Scale Aerodynamics Complex
n.mi.	nautical mile
OARF	Outdoor Aerodynamic Research Facility
OEI	one engine inoperative
OGE	out-of-ground effect
PAX	passengers
PFRT	preliminary flight rated test
PL	payload, pounds
PR1	productivity index
psf	pounds per square foot
q	dynamic pressure, psf
rpm	revolutions per minute
RSRA	Rotorcraft Systems Research Aircraft
SFC	specific fuel consumption, lb/hp-hr
shp	shaft horsepower
SL	sea level
SOW	statement of work
sq ft	square feet
STOL	short takeoff/landing
TDT	transonic dynamic tunnel
TERPS	terminal and enroute procedures
TF	Tiltfold
TFS	Tiltfold System
TR	Tiltrotor
TW	Tiltwing
V_{cr}	design cruise speed, knots
VDTR	Variable Diameter Tiltrotor
V_H	maximum velocity, knots
VTOL	vertical takeoff/landing
wt	weight

PREFACE

This report documents the results of work performed by Bell Helicopter Textron, Incorporated (BHTI) under Contract NAS2-13072 entitled Technology Needs for High Speed Rotorcraft. This final report covers all three technical tasks specified in the SOW. The NASA-Ames Flight Research Center Contracting Officer's Technical Representative was Mr. Peter Talbot. The BHTI Project Engineer for this study was Mr. Jack DeTore, Staff Engineer, Product Definition Group; Mr. John Magee, Director.

Preparation of the substantiating data and compilation of the final report was coordinated by Mr. Scott Conway of the Bell Helicopter Preliminary Design group. Identification of the critical technologies for the 450-knot cruise speed goals of this study presented in the Appendix are by Mr. Jack DeTore.

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SUMMARY

The objectives of this high speed rotorcraft technology evaluation are threefold: to identify technologies needed to extend the cruise speed capability of rotorcraft, to identify technology issues which must be resolved to obtain technical goals, and to propose a technology plan that takes the technical disciplines to a state of readiness enabling applications with reasonably low risk.

The spectrum of rotorcraft is examined with the intent of selecting two or more configurations for a more detailed analysis. Basing the selection on hover performance, speed capability, mission profile criteria, a Bell-defined index of productivity, conversion criteria, and an assessment of current feasibility of technologies, three configurations were suggested as baselines for further analysis: a 15-passenger commercial tiltfold, a 30-passenger commercial tiltfold, and a 30-passenger commercial tiltrotor. The two tiltfold aircraft addressed the NASA cruise speed specification of 450 knots. The 30-passenger tiltrotor was aimed at 375-knot cruise speed (productivity speed peak).

Each of the commercial configurations is defined to a conceptual level adequate for sensitivity studies. Sensitivity studies investigated the effect of weights reductions, performance improvements, aeroelastic stability improvements, and flight technology improvements. Each category was investigated individually and the combined effect of all advances was applied to all configurations. Partial derivatives are taken on each technology to determine which improvement had the most impact on the advanced technology configurations.

Noting the technologies with the most impact, technology tasks are then identified to resolve the technology issues such that the configurations might be implemented with a relatively low level of risk. In addition to the general technologies that improve the productivity of any rotorcraft, the critical rotorcraft technologies essential for addressing the 450-knot goal are specifically identified.

For the tiltrotor, critical technology would be demonstrated by powered wind tunnel tests in which a subscale proprotor system generates productive propeller efficiencies up to .7+ Mach. Additional unpowered wind tunnel tests with the same aeroelastically designed rotor on a semispan wing-pylon assembly, having a suitable structure for helicopter mode and maneuvering flight, would demonstrate satisfactory aeroelastic speed margins.

For the tiltfold, two elements are needed for critical technology demonstration: 1) a large scale folding proprotor (i.e., 25-foot diameter) wind tunnel test with a lightweight design based on lessons learned from the successful 1972 NASA tests, based on modern structures, and optimized for hover, and 2) demonstration of the fan-shaft coupling scheme which is critical to a productive convertible engine.

INTRODUCTION

Past and recent efforts have sought to combine in a single concept the hover efficiency of the helicopter with the high speed capability of fixed wing aircraft. These attempts encompass categories known as compound helicopters, stopped rotors, stowed rotors, tiltrotors, tiltwings, and various hybrid concepts. For some concepts, limited experimental data exists while others are based strictly on conceptual design analysis. Bell Helicopter's part in vertical takeoff/landing (VTOL) flight development began in the 1944-1946 period. Arthur Young, inventor of the two-bladed rotor used on early Bell helicopters, pioneered flying model experiments with tail-sitting, tilt-body configurations. The subsequent level-body, tiltrotor era began at Bell with studies by Lichten in the late forties which led to the XV-3 "Convertiplane." This concept and variants of it have been the basis of much of the original work by Bell over the years. Underlying this sustained effort had been the promise of superior productivity among contending VTOL types. An overview is presented in reference 1 of much of the pioneering work by Bell and others leading up to the rollout of the XV-15 tiltrotor proof-of-concept aircraft in 1976. That paper develops a productivity index much like the one used in this study for comparing the lift fan, tiltwing, tiltrotor, compound helicopter, and pure helicopter over a range of mission ranges from 40 to 1600 nautical miles (n.mi.). The tiltrotor won. Another measure was also addressed: response time. It was shown, for example, that in some VTOL missions the Harrier wins. That measure recognized that minimum trip time helped the user achieve his goal even if peak productivity occurred at slower speed. The tiltfold variant of the tiltrotor was explored to provide options that blend speed and productivity for such applications. As technology advances, reappraisement of measures of efficiency, like this study, are needed. Current and future developments in the technologies related to composite structures, advanced aerodynamics, digital flight controls, advanced propulsion concepts, and aeromechanics prediction capability may allow these concepts to achieve the goal of sustained high speed flight more efficiently. It is the goal of this study to determine which technologies are critical to the advancement of rotorcraft to a design cruise speed of 450 knots by the year 2000.

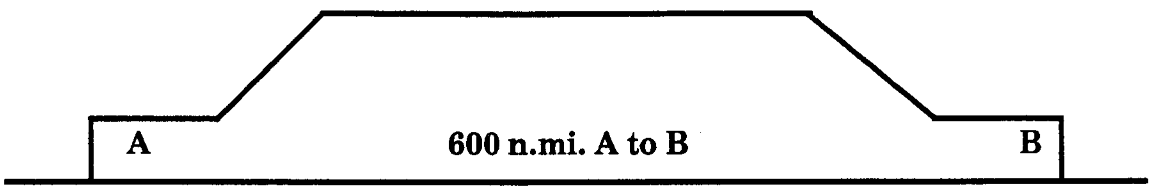
Specifically, the objective of this study is to identify the technologies needed to greatly extend the cruise capabilities of rotorcraft (to high subsonic speeds) without significant compromises to the low speed attributes; to identify critical technical issues which must be resolved in order to accomplish predetermined performance goals; and to identify a technology plan that takes the technical disciplines to a state of readiness that would enable application with relatively low risk.

The study comprises three tasks. The first task is a broad assessment of a variety of configuration concepts and associated technology and the selection of two of the most promising concepts for further study. The second task is a more detailed investigation of the critical technologies for concepts recommended in Task 1. The final task is to establish a technology plan such that the benefits identified in Task 2 may be realized. The next three sections in the body of this report cover the results of the three tasks respectively.

INITIAL TECHNOLOGY ASSESSMENT AND CONCEPT DEFINITION

To assess the impact of emphasizing various technologies, a baseline configuration must first be defined. This involves selecting a mission and an appropriate configuration to fulfill the mission requirements. This technology assessment called for a configuration with efficient hover qualities, comparable to a helicopter, and an efficient, high speed cruise. The cruise speed range of interest was 350 to 500 knots with a goal of 450 knots specified.

From the statement of work (SOW), two civil mission payload-profiles were selected. The flight profile is shown in figure 1. One payload-profile was for a 15-passenger, 3000-pound (lb) payload configuration and the other was for a 30-passenger, 6000-lb payload configuration. Both civil aircraft were required to hover OEI (one engine inoperative), at sea level (SL), International Standard Atmosphere (ISA) + 15° Celsius (C) in addition to conforming to Federal Aviation Regulation (FAR) Part XX requirements.



- Hover 1 minute, OGE, SL, ISA + 15°C (OEI capable)
- Convert to cruise configuration, SL, ISA + 15°C
- Climb to cruise altitude for best speed, ISA
- Cruise at altitude, ISA, at design cruise airspeed
- Descend to SL, ISA
- Convert to hover configuration, SL, ISA + 15°C
- Hover 1 minute, OGE, SL, ISA + 15°C
- Land with 10% mission fuel reserve
- Range, time, fuel credit for all segments

Figure 1. 15-Passenger and 30-passenger civil mission profile.

Examining the spectrum of rotorcraft, the helicopter and the compound helicopter were eliminated on the basis that they were unlikely to attain the 350-knot minimum. Similarly, fanjets and tiltfans were eliminated based on their poor hover qualities making uneconomical the capability of OEI hover in a twin-engine aircraft. The X-wing was eliminated based on its unproven control concept and Bell's belief that vehicle development would be unlikely by the year 2000. Since the tiltfold is essentially a tiltrotor up to the point of its conversion from forward proprotor flight to forward fan flight, it is believed that the tiltfold has a much better chance of succeeding than the X-wing. In addition, sufficiently precise and economical methodologies are not currently available at Bell to adequately simulate the X-wing's projected weight and performance. Therefore, the remaining vehicles are: the tiltfold, the variable diameter tiltrotor, the tiltrotor, and the tiltwing. Additional details are presented in the interim report covering Task 1 (see the Appendix).

To compare the various configurations, a measure of efficiency is required. Commercial configurations are very sensitive to weight, range, and time: how much can be moved how far in what amount of time and what does it cost. For this stage of conceptual design, empty weight and fuel are used as measures of cost. One pound of empty weight has approximately the same influence on cost as one pound of fuel per trip within the first few years of aircraft use. This point occurs early in the life of the aircraft roughly where the number of trips flown equals the cost per pound of empty weight divided by the cost per pound of fuel. Both payload and range are specified in the SOW, therefore the "effectiveness" of all concept candidates having the same design cruise speed is essentially the same. The resulting index of productivity is shown below.

$$\text{PRODUCTIVITY INDEX} = \frac{\text{PAYLOAD} \times \text{BLOCK (RANGE/TIME)}}{\text{(FUEL + EMPTY WEIGHT)}}$$

The various configurations were compared on a productivity vs design cruise speed basis. Comparisons showed that tiltrotors were the most productive configuration up to 395 knots, the tiltwing to 425, and the tiltfold aircraft proved the most productive for the remainder of the speed range considered. With the assessment used of current technology, the tiltfold was the only configuration capable of the 450-knot design cruise speed goal (see figs. 2 and 3). Similar trends and crossover points between concepts occurred for both the 30-passenger and the 15-passenger configurations.

Qualitatively, the tiltwing's low-speed and conversion handling qualities would not warrant further consideration of this concept in comparison with the tiltrotor and the tiltfold concepts (refs. 2 and 3). More detailed analyses would show and previous flight programs have demonstrated that slow, 9- to 10-degree (deg) approaches would be needed by the tiltwing. This inherent tiltwing trait would adversely affect "noise footprints" in the approach area as well as reduce productivity due to increased approach time not accounted for in this study.

The variable diameter tiltrotor was analyzed only up to speeds of 390 knots. This is because in the cruise configuration, the optimum diameter decreases, effectively increasing the advance ratio for a constant rotational speed and forward flight speed. If the rotational speed is increased in order to decrease the advance ratio, helical tip Mach boundaries are exceeded. For thrust levels consistent with the gross weights considered in this study, propulsive efficiency at advance ratios greater than 4.34 and helical tip Mach numbers greater than 0.93, data for propellers capable of hover flight are unavailable. Instead of speculating at propulsive efficiencies beyond said boundaries, analyses were terminated.

Tiltfold aircraft in the two size classes were recommended to fulfill the study requirement for defining two concept-mission combinations for further study. This recommendation was based on the fact that they were the only two aircraft capable of attaining the 450-knot design goal under current technology definitions. In addition, it was believed that the

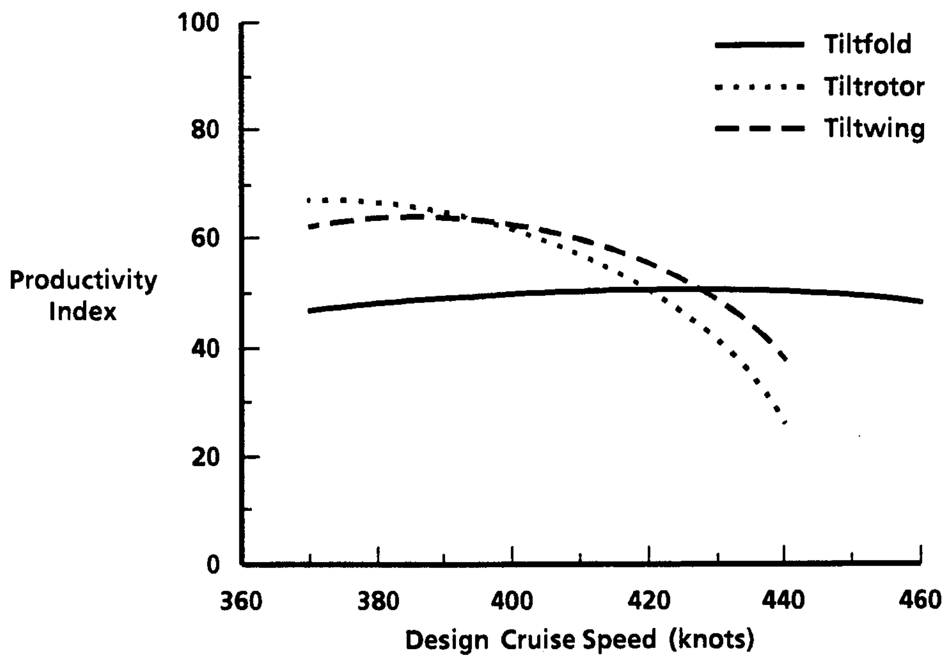


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Figure 2. Optimal 30-passenger designs.

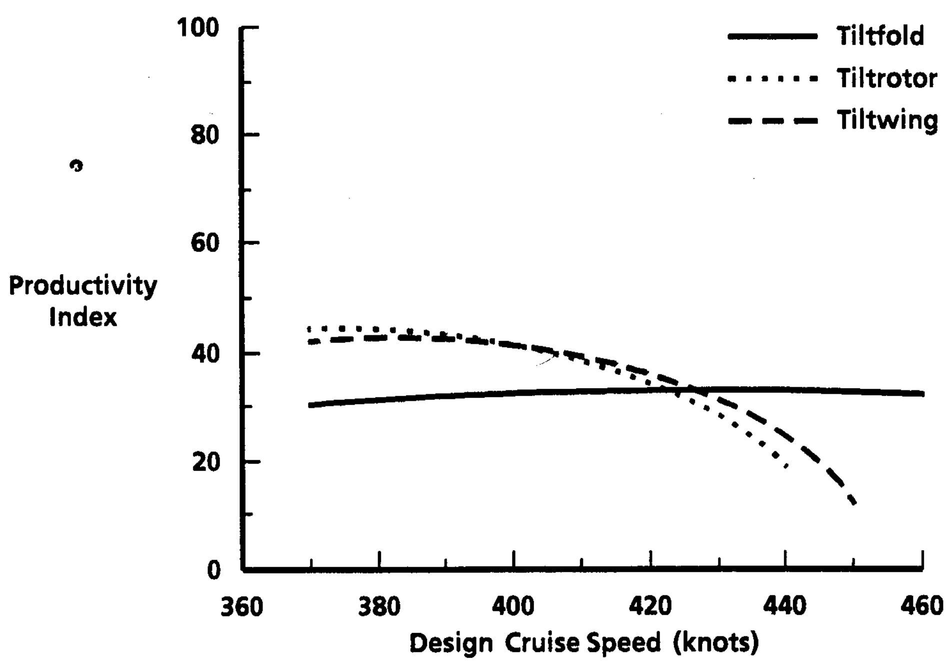

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Figure 3. Optimal 15-passenger designs.

tiltrotor could achieve the 450-knot design speed goal, providing that certain technology advances were realized. Therefore, the most productive tiltrotor, which happened to be the 375-knot, 30-passenger configuration, was also recommended as a baseline for the Task 2 technology evaluation in the interim report (Appendix).

TECHNOLOGY EVALUATION FOR THE SELECTED CONCEPTS

The technology evaluation was divided into three parts. The first part involved defining the three configurations to a conceptual level adequate to perform sensitivity studies. Advanced technologies were applied to aircraft with a current technology baseline (defined later in detail). Then, all technology advancements were applied to all configurations and the spectrum of rotorcraft was swept again to determine combined advances. Additionally, partial derivatives of the advanced technology aircraft configurations were taken to assess the impact of particular technologies on the new configurations (i.e., what would happen if certain technology advances did not occur).

Concept Definition

Utilizing the three commercial configurations recommended in Task 1, a preliminary design study was conducted. The optimal design point, based on productivity index, was chosen from a database of several synthesized designs and elaborated upon. The following tables (1-3) present the dimensional, weights, and performance data accordingly. Three-view representations are shown in figures 4 through 6, and performance plots in figures 7 through 12.

Since the tiltfold and tiltrotor aircraft are both fairly conventional configurations, a summary of the precise component locations aside from those shown in three-view was not deemed necessary to evaluate the feasibility or productivity of these aircraft.

To determine aircraft drag, the coefficient of drag for each component is calculated and multiplied by the appropriate area resulting in component f_e (equivalent flat plate area). The component f_e's are then summed to provide an aircraft f_e. Coefficient calculations and area calculations are based on techniques found in Hoerner's (ref. 4). A summary of the component f_e values is shown in tables 4 through 7.

Table 7 shows various pertinent performance figures. Note that the two tiltfold aircraft are designed at 450 knots and the tiltrotor at 375 knots. The engine baseline is the Allison T-406, and convertible engine performance figures are based on the Allison (ref. 5) and General Electric (ref. 6) Precursor Studies done under contract to NASA-Lewis. Propulsive efficiency is based on V-22 data.

Table 1. CURRENT TECHNOLOGY DESIGN POINT SUMMARY DESCRIPTION

	Tiltfold	Tiltfold	Tiltrotor
No. Passengers	15	30	30
Payload, lb	3000	6000	6000
Distance, n.mi.	600	600	600
V_{cruise}, knots *	450	450	375
Cruise Altitude, kft	20	15	15
Block Time, hr	1.5	1.5	1.7
Design Gross Wt, lb	40,713	56,563	38,565
Empty Wt, lb	29,565	39,364	26,356
Rotor Diameter, ft	36.0	42.0	35.0
Takeoff shp/Eng	7897 **	9391 **	7474
Fuel Wt, lb	7583	10,443	5574
Productivity Index	32	48	68

* Approximate speed for best productivity (figs. 2 and 3).

** Shaft power rating from a convertible engine capable of much higher fan cruise power.

Table 2. GEOMETRY SUMMARY

	15-TF	30-TF	30-TR
Wing Group			
Span (ft)	46	53.9	46.5
Root Chord (ft)	7.4	8.74	6.91
Tip Chord (ft)	7.4	8.74	6.91
Taper Ratio	1	1	1
Thickness/Chord (n.d., %)	16	16	22
Quarter Chord Sweep (deg)	-6	-6	-6
Dihedral (+up) (deg)	2	2	2
Aspect Ratio	6.24	6.17	6.74
Area (sq ft)	340.4	471.1	321.3
Horizontal Tail			
Span (ft)	20.5	24.28	19.12
Root Chord (ft.)	4.66	5.52	4.36
Taper Ratio	1	1	1
Thickness/Chord (%)	9	9	9
Quarter Chord Sweep (deg)	19	19	19
Dihedral (+up)(deg)	0	0	0
Aspect Ratio	4.4	4.4	4.4
Area (sq ft)	95.44	134.0	83.65
Vertical Tail			
Span (ft)	11.95	14.09	11.63
Root Chord (ft)	9.96	11.74	9.69
Tip Chord (ft)	9.96	11.74	9.69
Taper Ratio	1	1	1
Thickness/Chord (%)	9	9	9
Quarter Chord Sweep (deg)	43	43	43
Dihedral (+up)(deg)	0	0	0
Aspect Ratio	1.2	1.2	1.2
Area (sq ft)	119.04	165.4	112.7
Rotor Group			
Radius (ft)	18.0	21.0	17.5
Chord (in.) (3 blades/rotor)	31.8	37.5	30.9
Solidity	0.141	0.141	0.140
Disk Area (sq ft)	1018	1385	962
Twist (deg)	44	44	44
Body Group			
Fuselage Length (ft)	52.3	60.3	60.3
Fuselage Width (ft)	8.0	9.5	9.5
Fuselage Depth (ft)	8.0	9.5	9.5

Table 3. WEIGHTS SUMMARY

Component	15-TF		30-TF		30-TR	
	Wt (lb)		Wt (lb)		Wt (lb)	
Wing Group		2663.2		4071.1		2267.3
Rotor Group		4243.9		6133.7		2758.0
Rotor	2811.7		4110.4		2634.2	
Fold System	1303.5		1865.3		0.0	
Spinner	128.6		158.1		123.8	
Tail Group		616.9		932.8		557.1
Vertical Tail	371.4		558.1		351.3	
Horizontal Tail	245.6		374.7		205.9	
Body Group		4544.8		6097.6		4980.5
Pressurization Penalty	845.7		1093.1		1093.1	
Floor Penalty	322.8		456.3		456.3	
Fuselage	3376.3		4548.2		3431.1	
Alighting Gear Group		990.0		1196.3		959.4
Main Landing Gear	724.2		874.6		702.0	
Aux. Landing Gear	265.8		321.7		257.5	
Nacelle Group		1212.3		1602.0		1224.4
Nacelle	553.3		660.6		682.8	
Conversion Spindle	262.9		341.9		174.4	
Pylon Support	396.1		599.6		367.2	
Air Induction Group		108.3		124.4		103.7
Air Induction Sys.	81.4		95.0		77.5	
Bypass System	27.0		29.4		26.2	
Propulsion Group		4733.2		5634.6		2573.9
Engine	4070.9		4828.2		2013.4	
Exhaust System	31.0		34.8		29.9	
Ejector	38.8		45.0		37.0	
Starter	104.3		113.6		101.5	
Fuel System	488.2		612.9		392.0	
Drive System		3259.2		4417.8		2513.4
Centerbox	525.5		603.6		0.0	

Table 3. WEIGHTS SUMMARY (Continued)

Component	15-TF	30-TF	30-TR
	Wt (lb)	Wt (lb)	Wt (lb)
Transmission	1533.1	2225.0	1589.6
Transmission Supt.	137.8	214.5	127.8
Pivot Box	536.5	616.3	350.2
Mast	370.6	578.5	335.3
Pylon Shaft	48.7	56.2	34.2
Wing Shaft	107.0	123.7	76.2
Flight Controls Group	1902.5	2412.1	1806.7
Control Wire Wt	384.6	450.9	415.3
Rotating Conrols	362.8	462.0	348.0
Diameter Control	0.0	0.0	0.0
Flap Actuator	91.0	100.2	89.8
Rudder Actuator	34.1	41.4	33.0
Elevator Actuator	46.3	56.6	42.9
Rotor Actuator	510.9	679.2	486.1
Conversion Act.	472.8	621.9	391.7
Hydraulic Group	646.1	678.3	561.2
Electrical Group	510.3	531.5	518.7
Trapped Fluids	130.0	130.6	129.8
Fixed Equipment *	3842.0	5142.0	5142.0
Contingency	292.7	389.7	259.7
Total Empty Weight	29695.4	39494.7	26355.9
Useful Load	11017.6	17068.4	12208.6
Crew	435.0	635.0	635.0
Payload	3000.0	6000.0	6000.0
Fuel	7582.6	10433.3	5573.6
Gross Weight	40713.0	56563.1	38564.5
Empty Weight to Gross Weight Ratio	73%	70%	68%

Table 3. WEIGHTS SUMMARY (Concluded)

Component	15-TF	30-TF	30-TR
	Wt (lb)	Wt (lb)	Wt (lb)
* Fixed equipment includes:			
NASA Defined **	2900.0	4000.0	4000.0
Engine Controls	16.0	16.0	16.0
Accessory Gearbox	109.0	109.0	109.0
Cockpit Controls	217.0	217.0	217.0
Avionics	600.0	800.0	800.0
Total	3842.0	5142.0	5142.0

** NASA defined includes: APU, instruments, electrical, furnishings and equipment, air conditioning, anti-ice, load and handling equipment.

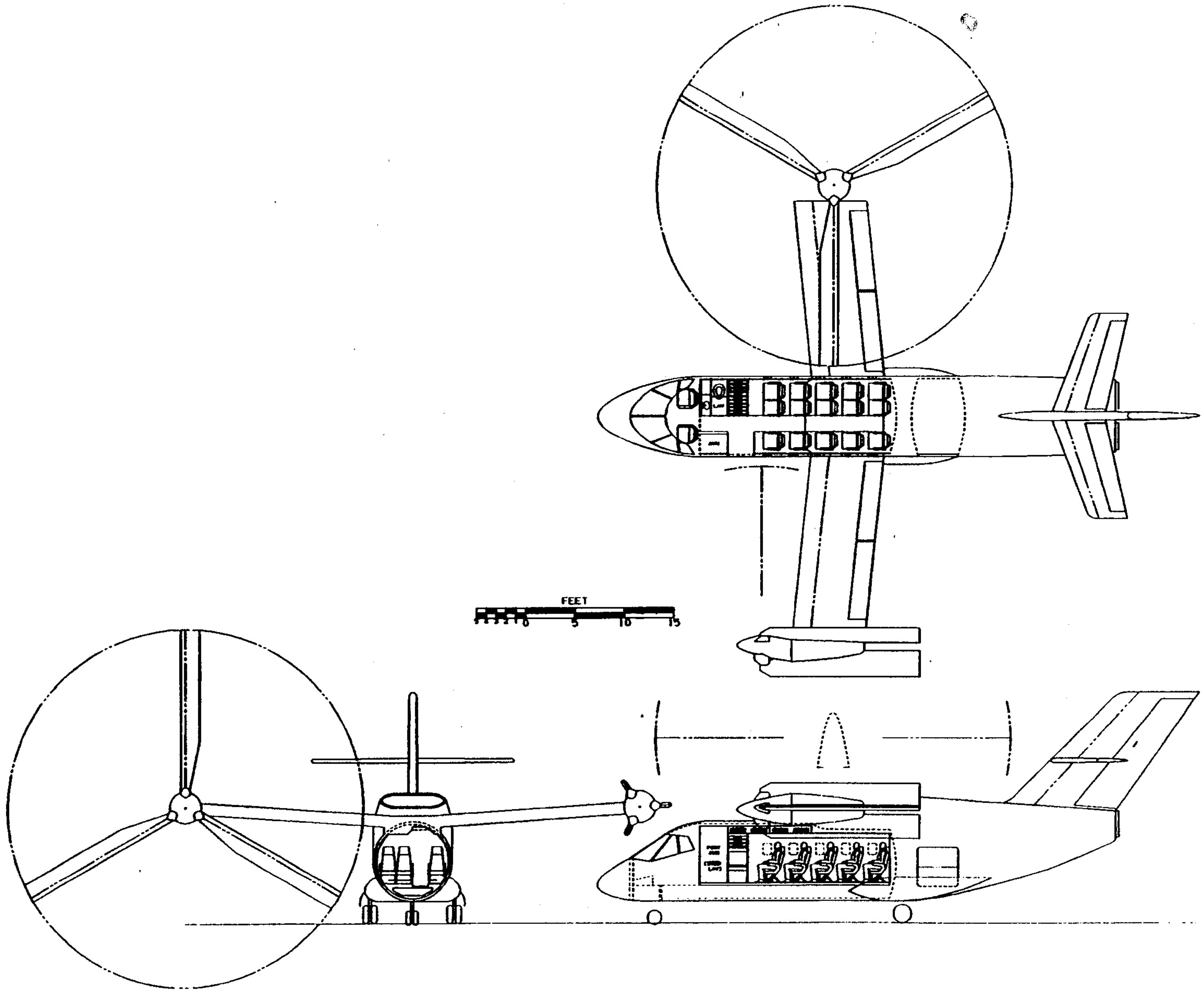

Figure 4. 15-Passenger tiltfold 3-view.

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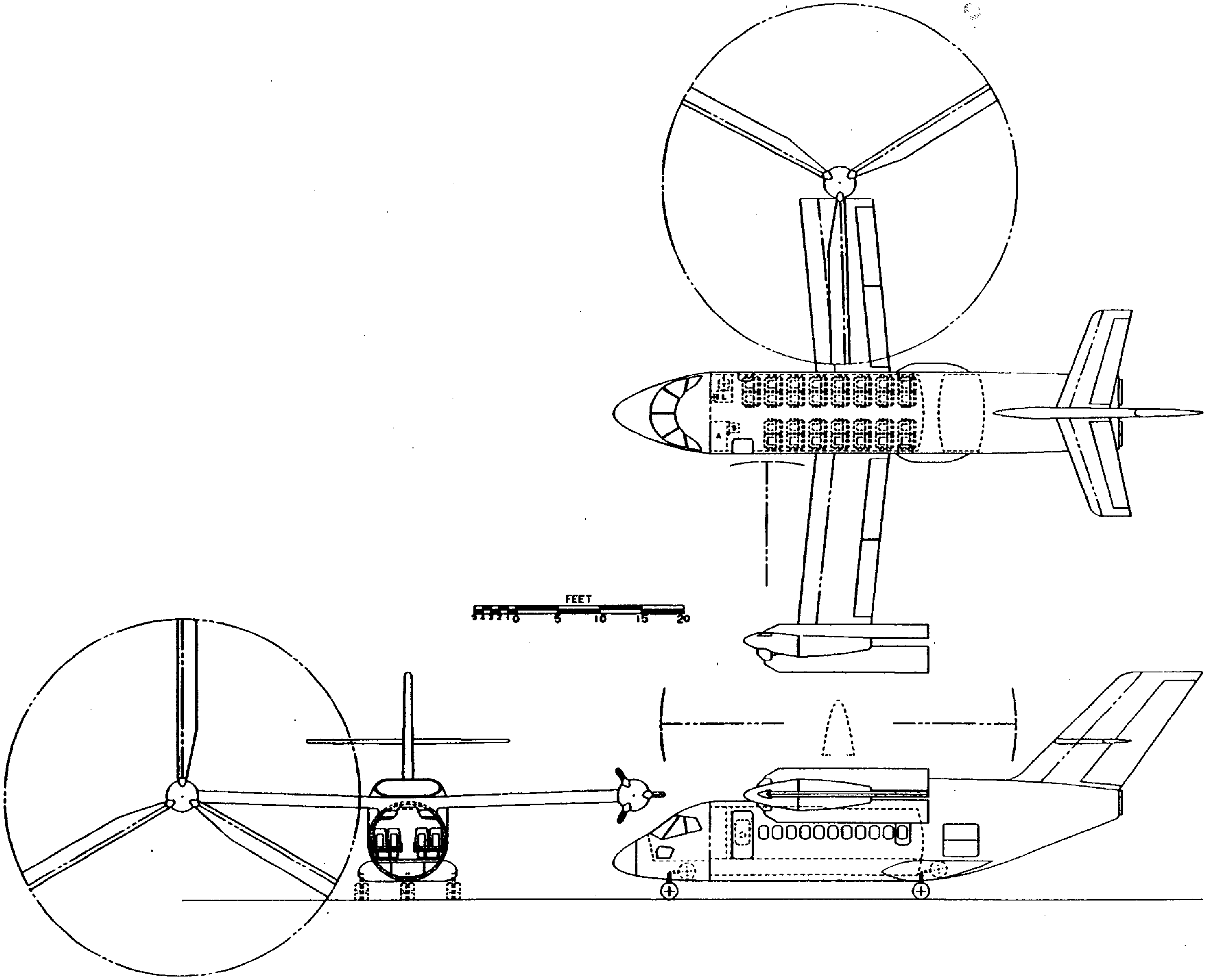

Figure 5. 30-Passenger tiltfold 3-view.

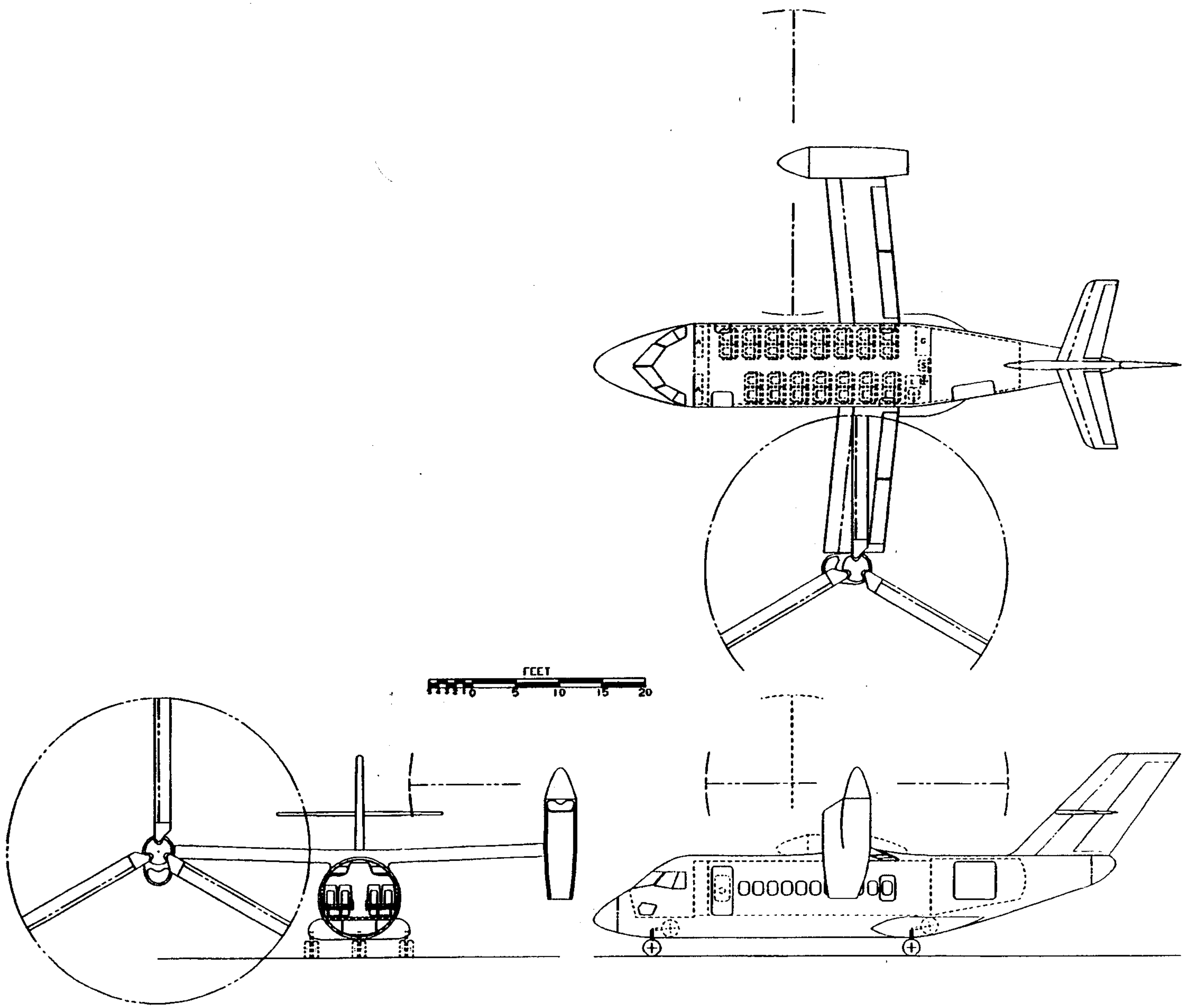

Figure 6. 30-Passenger tiltrotor 3-view.

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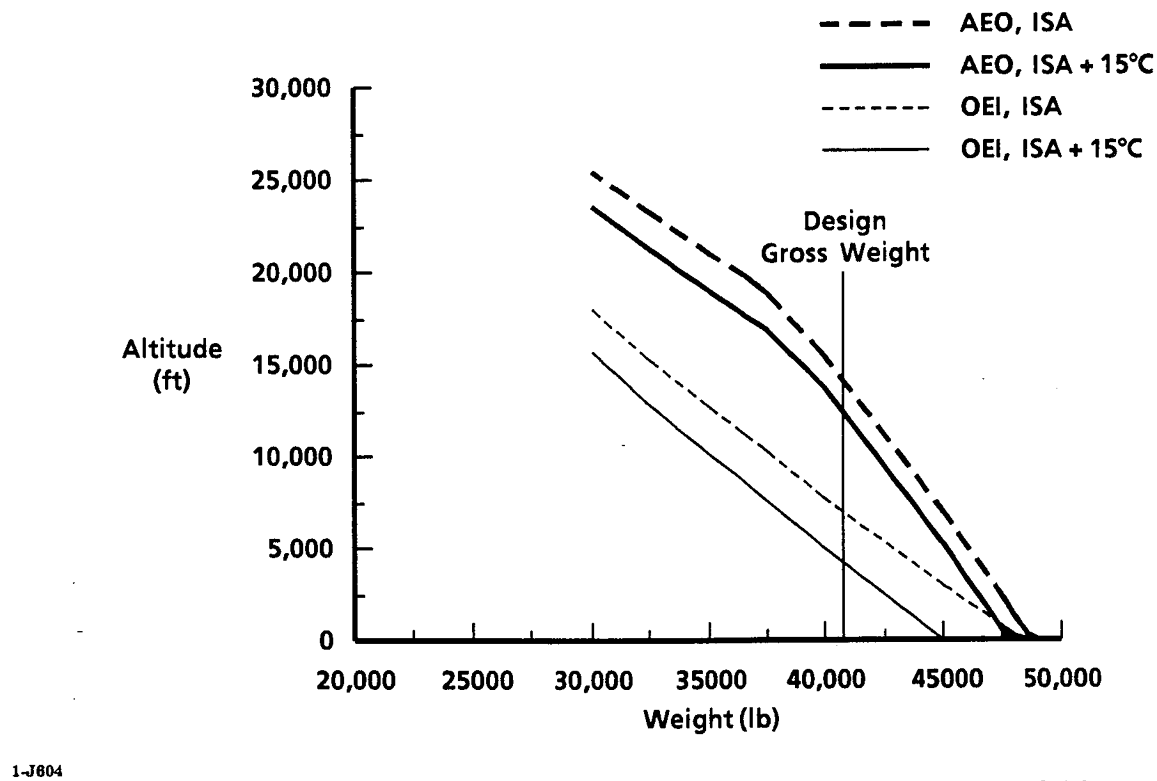

Figure 7. Hover ceiling (HOGE), 15-passenger, 450-knot tiltfold.

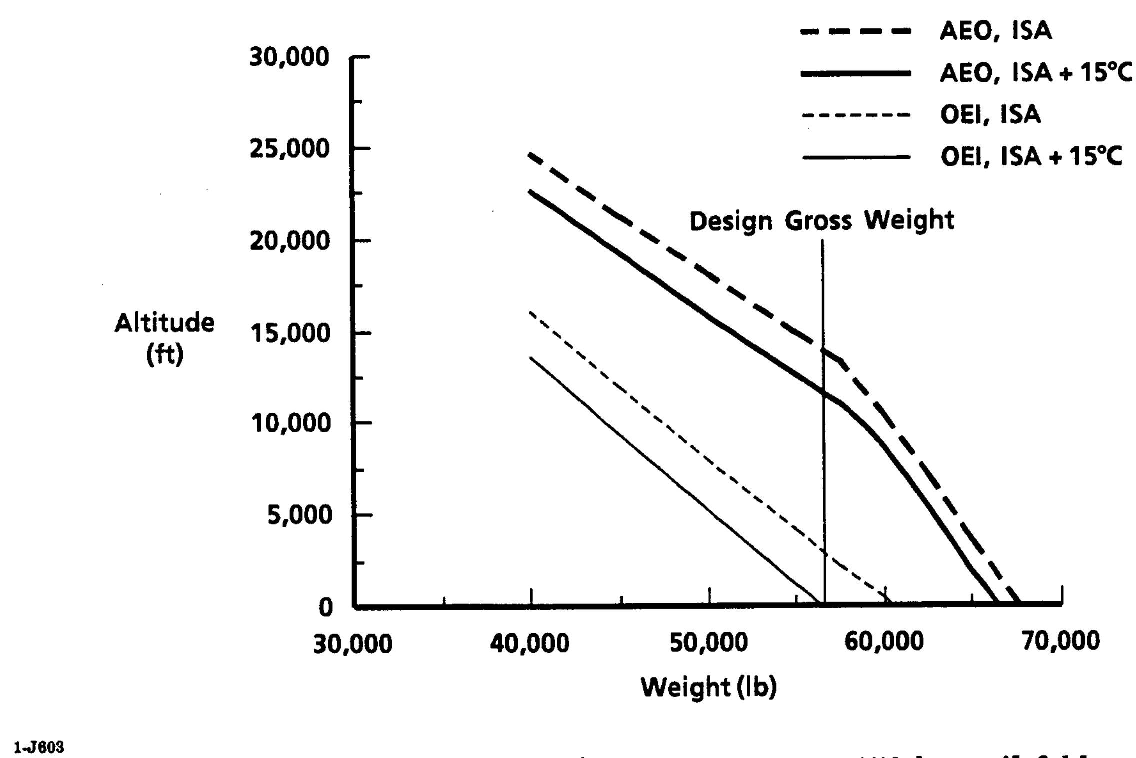

Figure 8. Hover ceiling (HOGE), 30-passenger, 450-knot tiltfold.

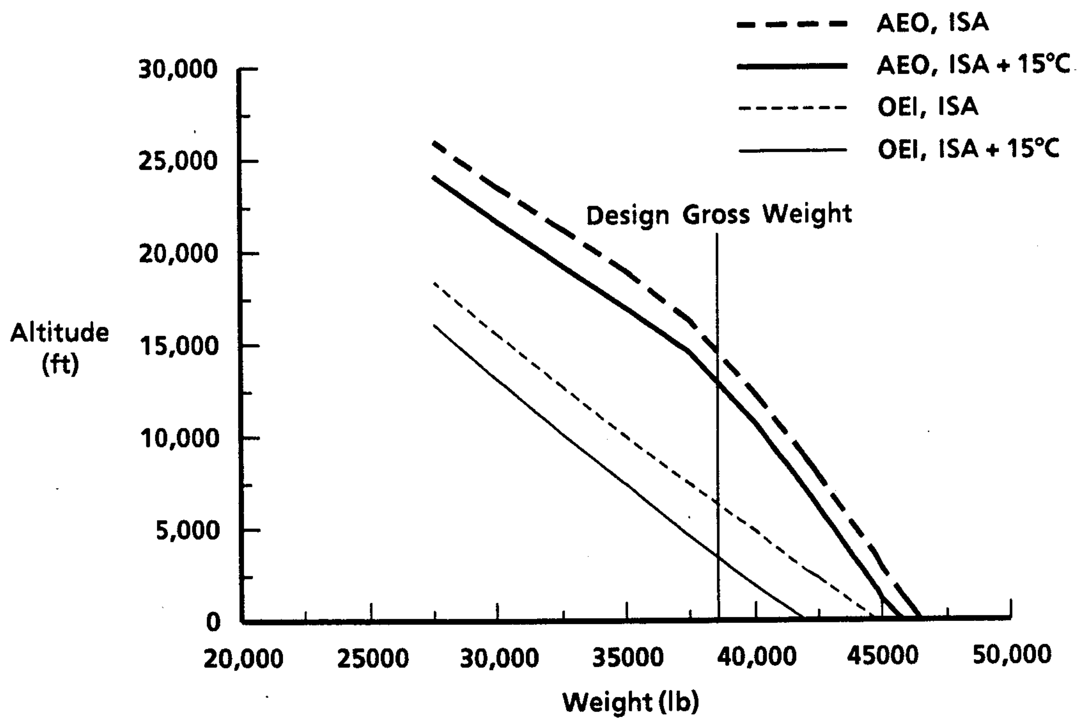

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Figure 9. Hover ceiling (HOGE), 30-passenger, 375-knot tiltrotor.

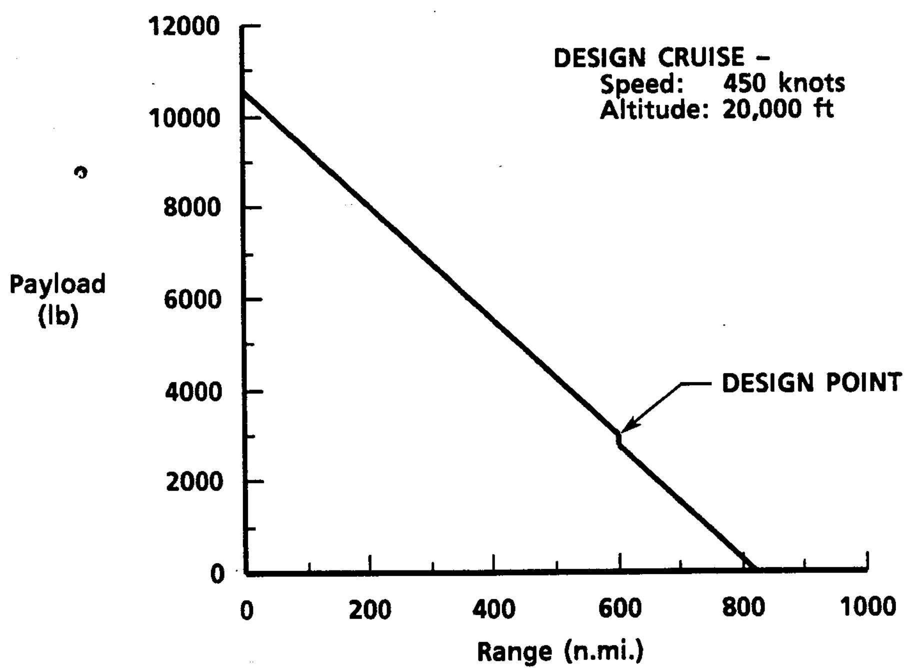

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Figure 10. Payload vs. range, 15-passenger tiltfold.

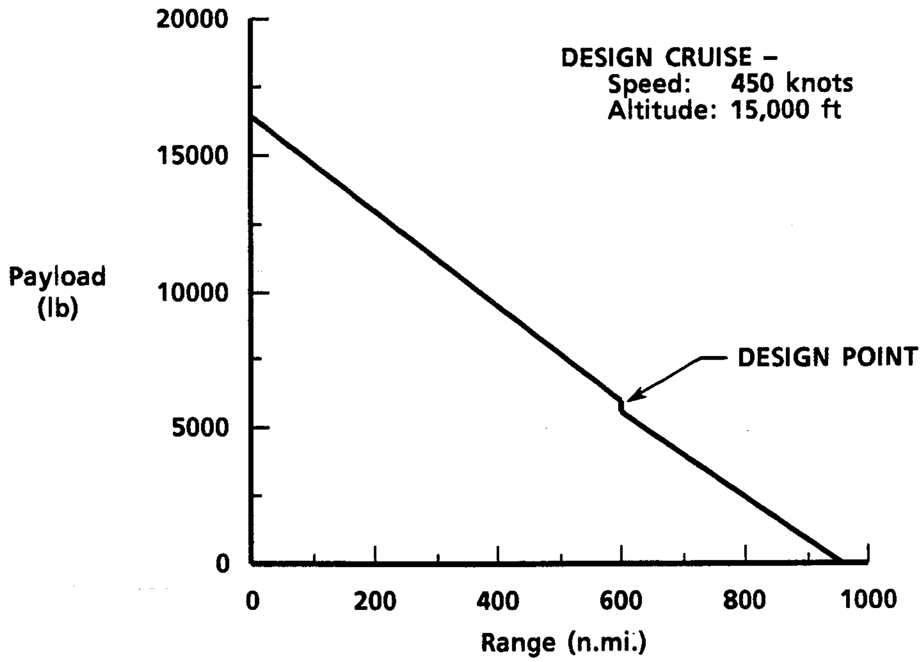

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Figure 11. Payload vs. range, 30-passenger tiltfold.

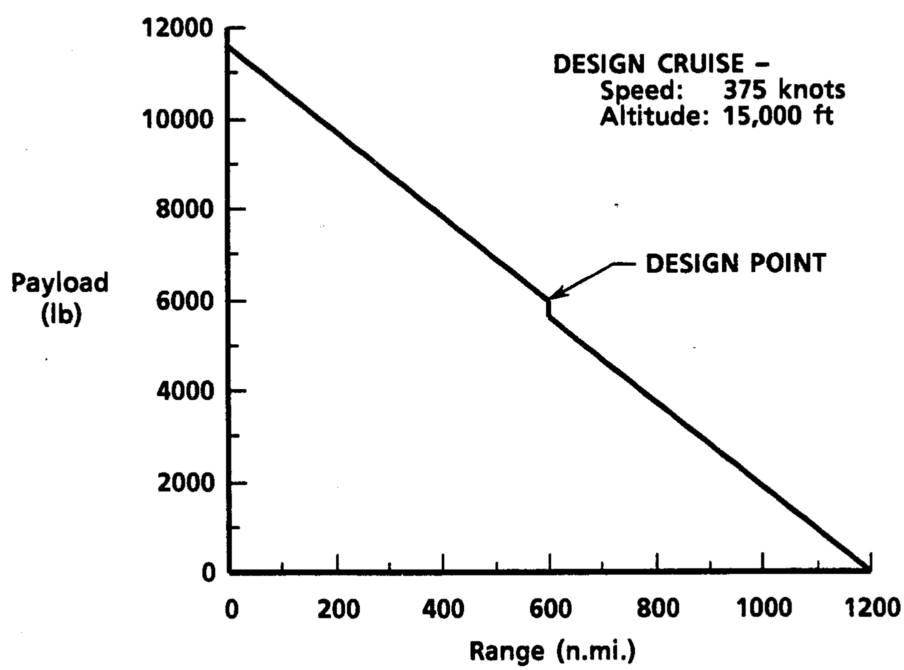

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Figure 12. Payload vs. range, 30-passenger tiltrotor.

Table 4. DRAG SUMMARY, 15-PASSENGER TILTFOLD

Component	Ref Area (sq ft)	C_D	f_e (sq ft)
Fuselage	1583.211	0.00193	3.061
Fuselage Base Drag	7.238	0.04000	0.290
Fuselage Roughness	*	*	0.306
Wing Fuselage Interaction	1.393	0.10828	0.151
Wing	280.271	0.00776	2.175
Wing Wave Drag	339.276	0.00244	0.829
Wing Roughness	*	*	0.217
Nacelle Wing Interaction	0.004	0.10828	0.000
Nacelle	302.272	0.00236	0.713
Nacelle Roughness	*	*	0.071
Folded Blade Exposed Surfaces **	550.069	0.00236	1.298
Horizontal Tail	114.528	0.00681	0.780
Horizontal Tail Roughness	*	*	0.078
Vertical Tail	142.853	0.00585	0.835
Vertical Tail Roughness	*	*	0.084
Miscellaneous ***			3.000
f_e Total			13.890

* Roughness drag is calculated as 10% of component (ref. 4).

** Estimated; 1972 wind tunnel tests of 25-ft fold proprotor deleted fold hinge cuffs for economy.

*** Miscellaneous includes sponsons, miscellaneous fairings and fittings, and additional avionic or load handling projections.

Table 5. DRAG SUMMARY, 30-PASSENGER TILTFOLD

Component	Ref Area (sq ft)	C_D	f_e (sq ft)
Fuselage	2074.26	0.00187	3.869
Fuselage Base Drag	9.71	0.04000	0.388
Fuselage Roughness	*	*	0.387
Wing Fuselage Interaction	1.96	0.10828	0.212
Wing	388.30	0.00738	2.867
Wing Wave Drag	471.33	0.00140	0.661
Wing Roughness	*	*	0.287
Nacelle Wing Interaction	0.01	0.10828	0.001
Nacelle	421.12	0.00226	0.952
Nacelle Roughness	*	*	0.095
Folded Blade Exposed Surfaces **	764.63	0.00226	1.728
Horizontal Tail	160.80	0.00651	1.046
Horizontal Tail Roughness	*	*	0.105
Vertical Tail	198.46	0.00560	1.111
Vertical Tail Roughness	*	*	0.111
Miscellaneous ***			3.000
f_e Total			16.819

* Roughness drag is calculated as 10% of component (ref. 4).

** Estimated; 1972 wind tunnel tests of 25-ft fold proprotor deleted fold hinge cuffs for economy.

*** Miscellaneous includes sponsons, miscellaneous fairings and fittings, and additional avionic or load handling projections.

Table 6. DRAG SUMMARY, 30-PASSENGER TILTROTOR

Component	Ref Area (sq ft)	C_D	f_e (sq ft)
Fuselage	2074.26	0.00193	4.011
Fuselage Base Drag	9.71	0.04000	0.388
Fuselage Roughness	*	*	0.401
Wing Fuselage Interaction	2.31	0.15880	0.366
Wing	255.73	0.00948	2.424
Wing Wave Drag	321.33	0.00	0.0
Wing Roughness	*	*	0.242
Nacelle Wing Interaction	0.15	0.15880	0.024
Nacelle	438.28	0.00243	1.066
Nacelle Roughness	*	*	0.107
Folded Blade Exposed Surfaces	N.A.	N.A.	N.A.
Horizontal Tail	100.38	0.00702	0.704
Horizontal Tail Roughness	*	*	0.074
Vertical Tail	135.30	0.00599	0.810
Vertical Tail Roughness	*	*	0.081
Miscellaneous **			3.000
f_e Total			13.698

* Roughness drag is calculated as 10% of component (ref. 4).

** Miscellaneous includes sponsons, miscellaneous fairings and fittings, and additional avionic or load handling projections.

Table 7. RATINGS, LOADINGS, AND VARIOUS PERFORMANCE VALUES

	15-TF	30-TF	30-TR
Wing Loading (psf)	120	120	120
Disk Loading (psf)	20	20	20
Blade Loading Coefficient	0.115	0.115	0.115
Helicopter Mode Tip Speed (fps)	780	780	780
Airplane Mode Tip Speed (fps)	601*	601*	601
Cruise Propulsive Efficiency	-	-	0.71
Cruise Speed (knots)	450	450	375
Cruise Altitude (ft)	20,000	15,000	15,000
Engine Shaft Power (shp, rated)	7897	9391	7474
Engine Static Thrust (lb, rated)	10,968	12,976	-
Wing $C_{L_{max}}$	1.8	1.3	1.8
Download/Thrust (%)	10.1	10.2	9.9
Design Limit Normal Flight Load Factor (g)	4.0**	4.0**	4.0**

* When initiating/completing conversion or loitering in airplane mode; normal cruise is with tip speed zero (blades folded).

** Until gust load conditions and others are analyzed, these aircraft are sized at a higher load factor than the 2.5g allowed for in FAR Part XX.

The tiltfold aircraft's conversion from helicopter to airplane mode is accomplished exactly as the tiltrotor aircraft's, but with the addition of the rotor stopping and folding process. A typical transition will occur between 120 and 200 knots. Once the conversion from helicopter to proprotor mode is made, the process may be continued by further use of the conversion control switch on the cyclic stick. After pylon conversion, further "beeping" of the control switch increases fan mass flow by varying pitch of the fan stator blades or by accelerating the fixed-pitch fan up to engine shaft speed. The increased demand for power tends to reduce the power turbine speed, which is then offset by proprotor governor reduction of the proprotor pitch. The drop in proprotor thrust is approximated by the increase in fan thrust; any deficiency in fan thrust is corrected by increased throttle setting to maintain the desired rate of climb at the transition airspeed. When the proprotor torque is essentially zero, the rotor may be decoupled from the drive train, feathered to a stop, indexed and then folded back and locked. These steps can be stopped and reversed at any point, and can be commanded by forward or reverse "beeping" of the conversion switch. The key functions required during transition are summarized in figure 13. The unpowered stop-fold process (and reverse) was analyzed and demonstrated with a 25-ft rotor in the NASA-Ames 40x80 foot wind tunnel in 1972. (refs. 7, 8, and 9). Loads correlation with theory and small-scale tests was good. Rotor fold/unfold runs were made up to angles of attack representing approximately 2g load factors.

Noise is an increasingly important facet of rotorcraft operation. Federal Aviation Administration (FAA) and International Committee Civil Aviation Organization (ICAO) noise standards require serious consideration in any new design. An ICAO noise evaluation usually requires a prototype aircraft and considerable testing, and is therefore beyond the scope of this study. However, a suitable approximation of sideline hover noise levels for tiltrotor configurations can be made for the three configurations in this study. Noise levels are based on tip speed, hover thrust, altitude, sideline distance, operational mode, and airspeed. For a hover altitude of 100 ft above ground level, and a sideline distance of 500 ft, noise levels in table 8 were estimated by scaling XV-15 and V-22 measured data.

Table 8. SIDELINE NOISE IN HOVER

	15-TF	30-TF	30-TR
Design Gross Weight, lb	40,713	56,563	38,565
Design Cruise Speed, knots	450	450	375
Sideline Noise, Level, dBA	90.2	92.6	89.8

The dBA unit in table 8 weights sound pressure levels to more nearly represent values of how loud noise sounds to the ear based on frequency content.

Since the subject aircraft each have the same design disc loading, tip speed, number of blades, and design blade loading coefficient, the results above show the effect of the design gross weight on noise level independent of the concept. Two questions emerge: 1) How can

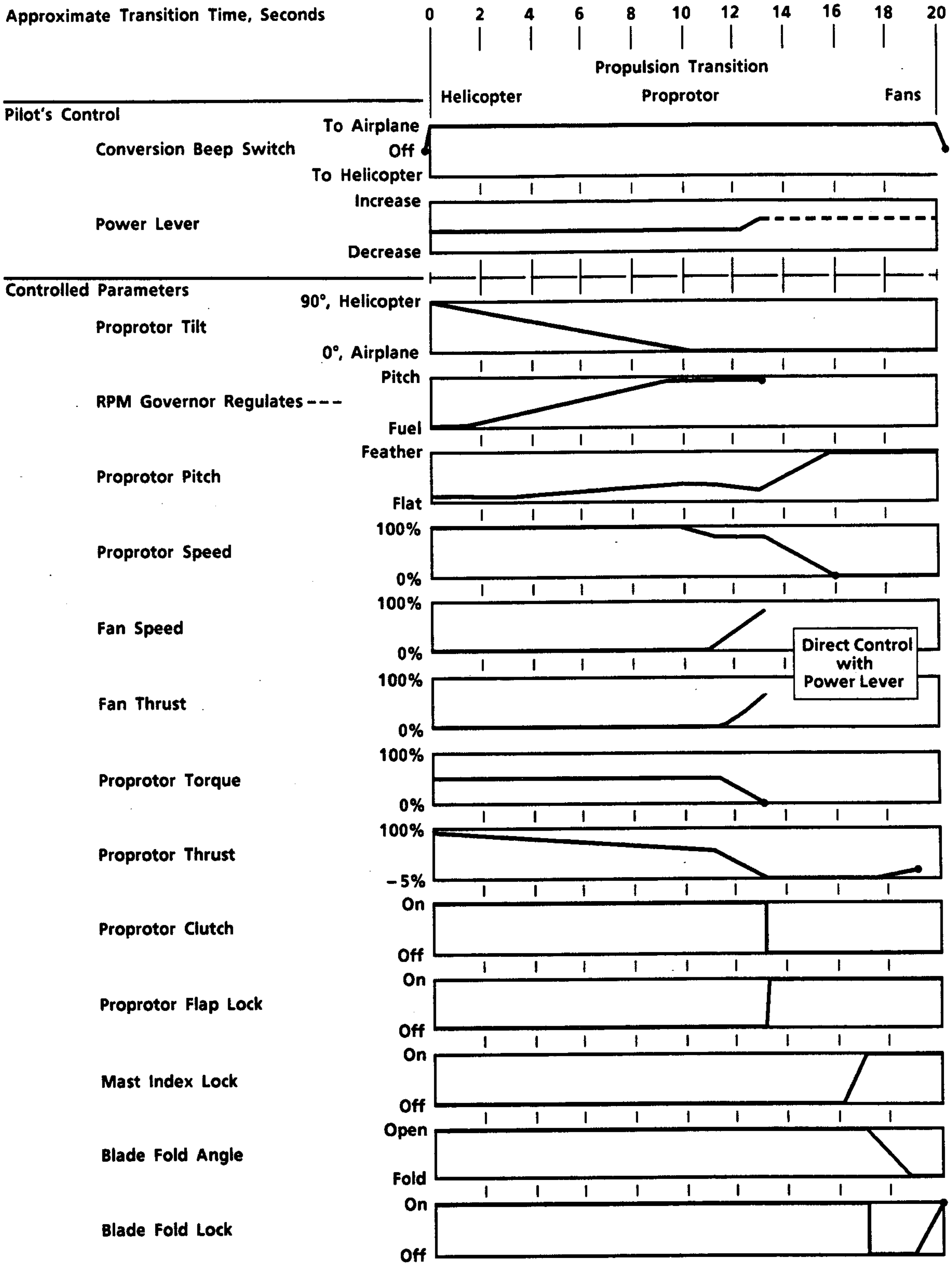

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Figure 13. Tiltfold conversion requirements.

the above levels be reduced productively? 2) How can the "required" and "reduced" values be productively reconciled? The rotor tip speed is a major factor in varying sideline noise level in hover. The sensitivity is discussed below.

Methodology and Sensitivity Analyses

Figures 2 and 3 show the spectrum of productivity vs. design cruise speed for the 30-passenger and the 15-passenger configurations, respectively. Each of these configurations represents the highest productivity point found for each respective speed. To attain these points, a PC-based Generalized Advanced Rotorcraft Program (GARP), developed under Bell IR&D, was used. GARP is a methodology that predicts a configuration to satisfy an input mission, certain defined geometries and payloads. It utilizes momentum theory for performance, refs. 4 and 10 for drag, V-22 flight test data and in-house simulations based thereon for propulsive efficiency, and the Bell Weights Technology Manual for Weights estimation. Some contraints are built-in to avoid overly ambitious excursions of basic design parameters. Quantitative adjustments are made, for example, to the statistical wing weight formulas to allow for aeroelastic stability criteria.

For each mission, a series of parameters were varied, including: disk loading, wing loading, thickness to chord of the wing, tip speed in hover, tip speed in cruise, cruise altitude, and design cruise speed. In the case of the variable diameter tiltrotor, the diameter ratio was also varied. All of these parameters were varied consecutively to determine the best combination of variables. In addition, several parameters were varied to determine the sensitivity of a given configuration to a specified value, e.g., wing sweep.

Several bounds were placed on the output. The advance ratio had to lie between 1.0 and 4.34; this was driven by available propulsive efficiency maps. The helical tip Mach number had to be less than 0.93; again due to data map constraints. The aircraft f_e had to be less than 60; configurations beyond an f_e of 60 were felt to be grotesque and beyond the accurate scope of our prediction routines. The gross weight had to be less than 200,000 lb; again, to minimize the departure of the synthesized point designs from the synthesis database for the sake of validity.

The following discussion shows the sensitivity of each configuration to the parameters varied. Since the 15-passenger and the 30-passenger tiltfold configurations had similar trends, the following study used the 30-passenger tiltrotor and the 30-passenger tiltfold "current technology" configurations as a baseline.

Figure 14 shows that for the tiltrotor aircraft the optimal disk loading for this level of technology is 20. The tiltfold has slightly higher productivities at lower disk loadings, but for geometry reasons a disk loading of 20 was selected, resulting in negligible effect on productivity.

Figure 15 indicates that the higher the wing loading the better the productivity. However, it was judged that wing loadings higher than 120 psf would unnecessarily increase the speed

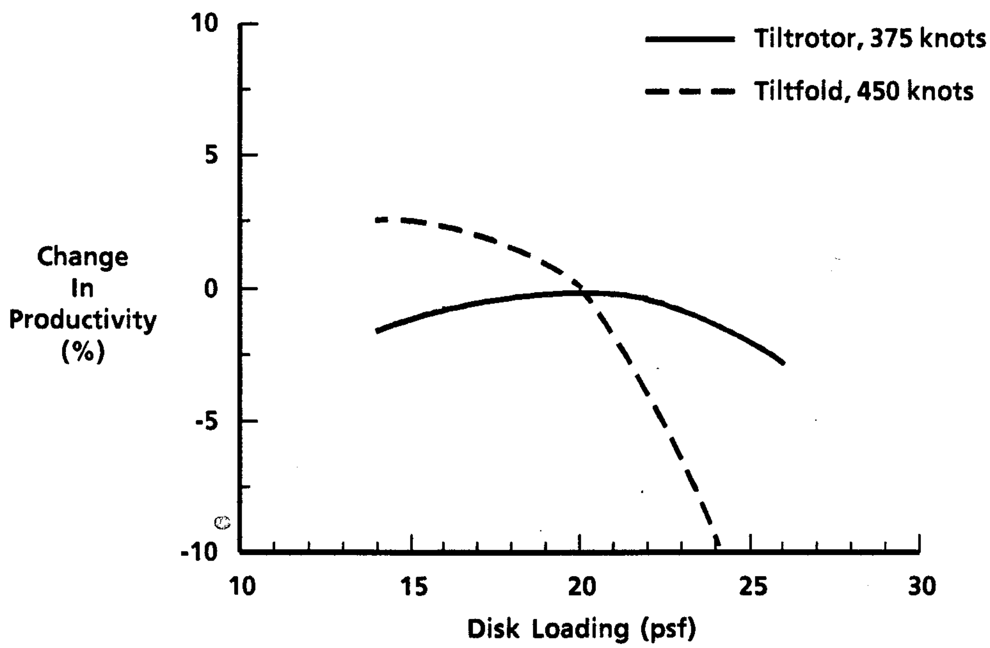

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Figure 14. Disk loading vs. % change in productivity.

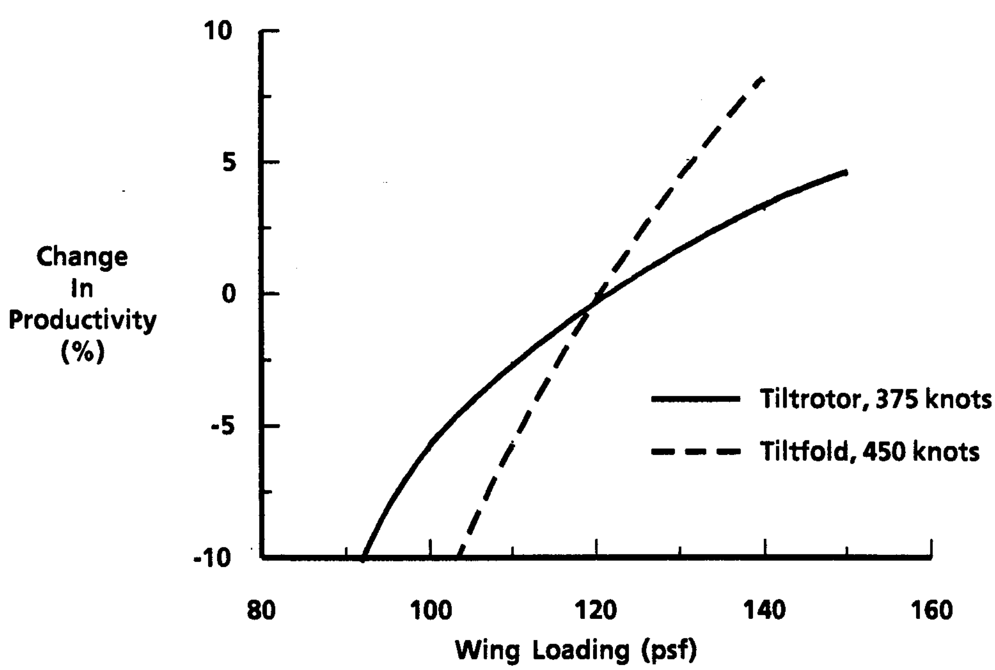

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Figure 15. Wing loading vs. % change in productivity.

range of the conversion corridor near the vertiport approach areas. Therefore, a wing loading of 120 psf was selected.

The aircraft zero-lift drag, f_e, estimated by the methodology used in this study, has compressibility effects represented as a function of the wing geometry at the cruise speed and altitude conditions. The compressibility effects are represented by a wing wave-drag increment given by Nicolai (ref. 10, fig. 11.10) for unswept wings based on work by NACA and Rand in references 13 and 14. These data are modeled as parametric curve fits which are functions of wing thickness, aspect ratio, and flight Mach number. A correction is made to flight Mach number in the data lookup for this function to allow for sweep variations in the range of + to −10 degrees. The incompressible wing drag components are estimated including sweep as an input parameter. These are based on Bell studies and wind tunnel tests of V-22 type airfoils over a range of thickness from 16 to 23%. Using the simple method described above leads to resonable correlation of wing section drag until high thicknesses and high subsonic Mach numbers are reached. At these conditions a "form" drag allowance (related to separation), not included in the simple method, is necessary for better correlation. All other components of aircraft drag are based on conventional methods referenced to wetted or frontal areas plus allowances for interference between major components. The wing "form" drag compressibility allowance would not have been exercised at the optimized wing thicknesses of 16% for the 30-passenger, 450-knot tiltfold design (cruise Mach number = .718 at 15K ft) and 22% for the 375-knot tiltrotor design (cruise Mach number = .598 at 15K ft). The drag divergence Mach numbers for the 16 and 22% airfoils at a nominal (C_L of 0.24 are approximately .72 and .66, respectively. The 15-passenger tiltfold flying at 20,000 ft would experience slightly higher compressibility drag with the 16% wing than predicted by the simple method. Figure 16 shows the effect of wing thickness on productivity of the 375-knot tiltrotor, and the 450-knot tiltfold, 30-passenger aircraft.

Looking at figure 17, it may be seen that the optimal hover tip speed is slightly higher than the one selected for the point design. However, a plot of noise reduction vs. tip speed (fig. 18) showed a potential savings of 1.2 dBA for a reduction of 20 feet per second (fps). Figure 18 assumes hover at the baseline gross weight, at constant altitude, and constant sideline distance. Blade loading coefficient is maintained by modifying rotor blade area such that tip speed is the only variable. Hence, to alleviate noise and to provide a wider compliance margin with minimal loss of productivity, a design point hover tip speed of 780 fps was chosen. Minimizing approach and departure noise flyover footprints is strongly influenced by operational techniques that require additional simulation work. Steep approaches and departures to keep helicopter mode operations close to the vertiports are the main reasons for not going further with the tiltwing in this study.

Using the baseline hover tip speed and varying the ratio of cruise tip speed to hover tip speed, figure 19 shows an optimal design at 77% (601 fps). This tip speed would also be used by the tiltfold when in the airplane-mode, low-speed loiter range.

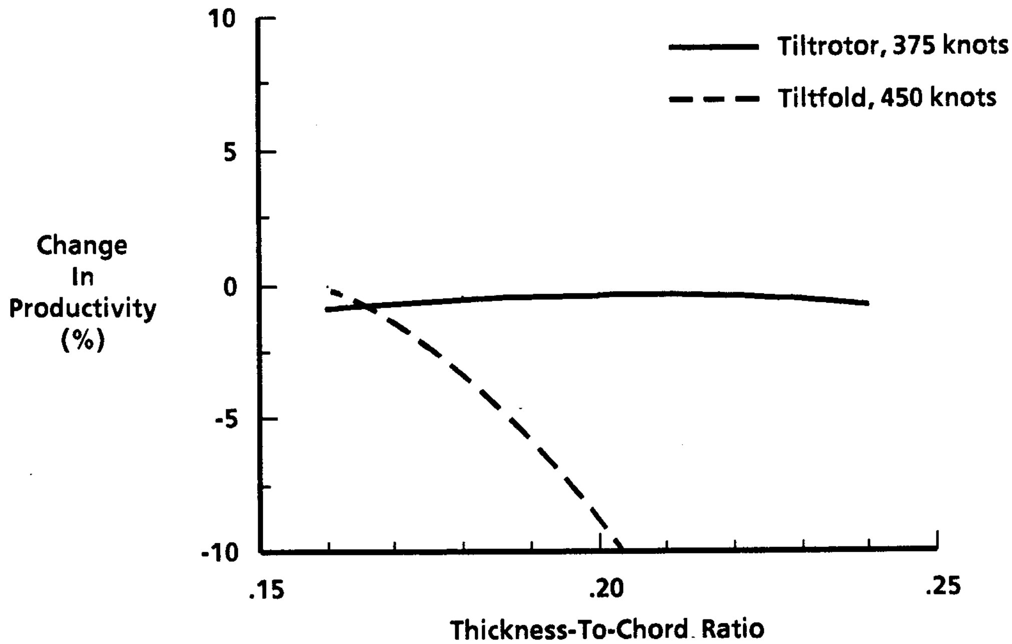

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Figure 16. Thickness-to-chord ratio vs. % change in productivity.

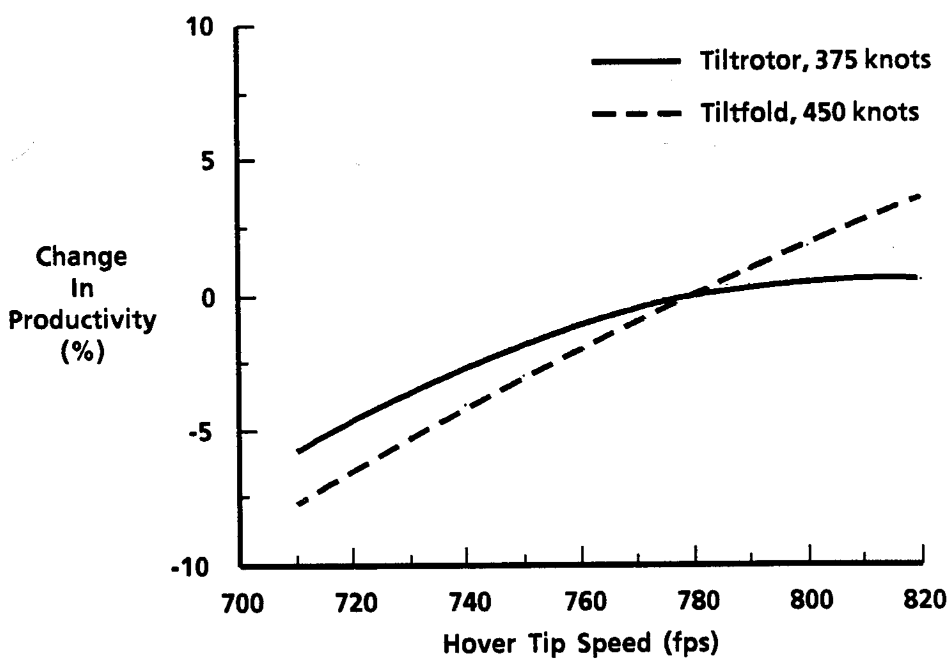

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Figure 17. Hover tip speed vs. % change in productivity.

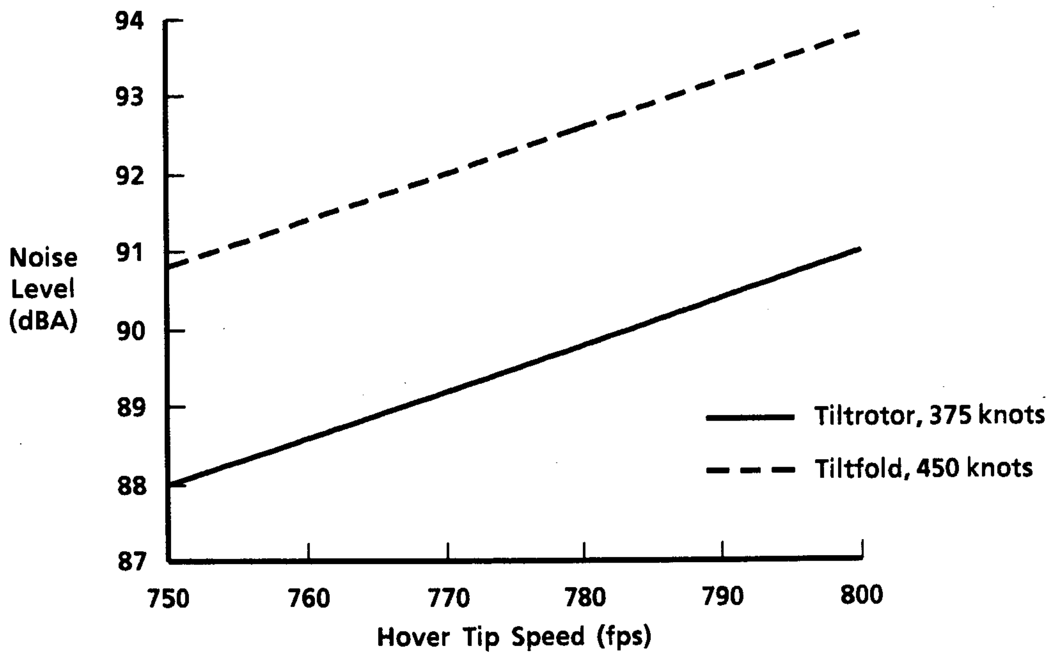

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Figure 18. Sideline noise levels vs. tip speed.

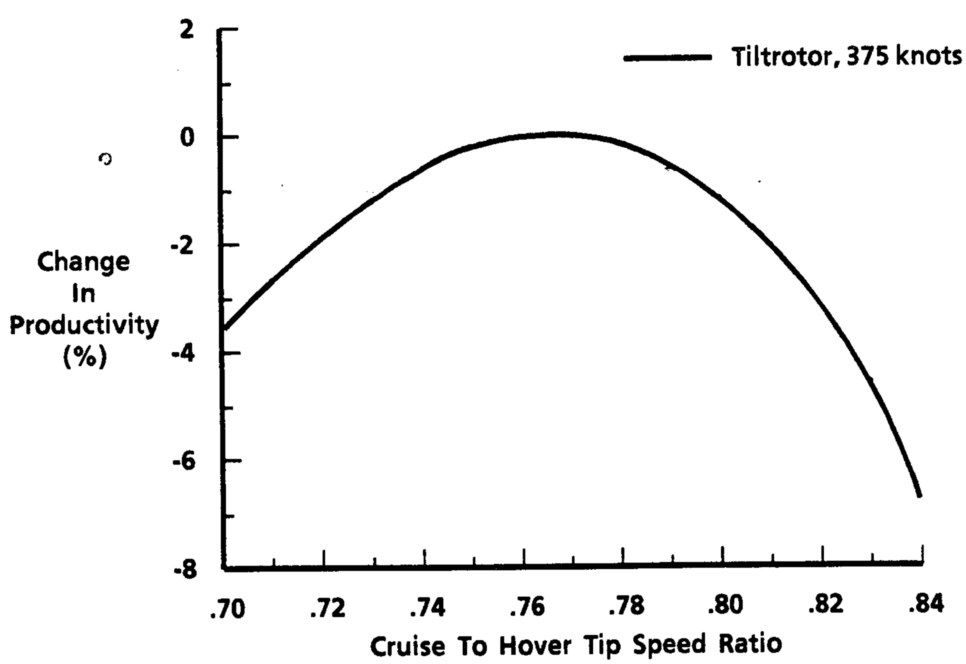

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Figure 19. Hover/Cruise tip speed ratio vs. % change in productivity.

An analysis of cruise altitude vs. productivity (fig. 20) showed that an altitude of 15,000 ft yielded essentially peak productivity for the tiltrotor and tiltfold.

Finally, an "offline" check of wing sweep angle vs. productivity (fig. 21) showed a relatively small productivity benefit from sweeping the wing much past 6-deg forward sweep. The effects of sweep, as predicted with the methods used, are more pronounced for the 450-knot tiltfold than for the 375-knot tiltrotor as would be expected from compressibility considerations. The productivity improvement of up to about 8% for −20-deg sweep is based on the favorable trade of predicted wing weight and mission fuel. However, the wing weight algorithms do not reflect aeroelastic stability effects due to sweep beyond the XV-15/V-22 range. If the wing is swept too far forward, a canard configuration is required. Since the interaction effects from the tip vortices of a canard as they impinge on the wing and the rotor in propeller mode is a little-investigated phenomena, it was considered that such a configuration could not be analyzed in keeping with criteria for "current technology." Likewise, the coupling of wing torsion and bending effects at large sweeps are not currently modeled in the synthesis code for aircraft with high wingtip masses and inertias. Keeping the sweep at values like those for the V-22 and XV-15 (6 to 6.5 deg) helps to avoid some of these potential uncertainties in the synthesis results. These uncertainties can form the basis of configuration R&D, but do not appear to be in the critical category for this mission.

Discussion of Current Technology Assumptions

For this contract, it was assumed that current technology meant technical capabilities and knowledge that would be applied to an aircraft were the first line drawn today (1991). For instance, the V-22 (in many cases) is considered "old technology;" however, the V-22 was used as a basis with appropriate modifying factors for certain components. The following is a description of specific components or parameters and their related level of technology.

The engine baseline is the Allison T-406. For convertible engine applications, the T-406 baseline specific weight in pounds per shaft horsepower output at hover is multiplied by a factor of 1.955 based on manufacturer data (ref. 5). The transmission assumes all advances from the Advanced Rotorcraft Transmission (ART) Program (ref. 11) with the exception of the "run hot" modifications.

Composite technology factors represent the ratio of weight from a metal to a composite component (i.e., weight savings due to material usage), and a summary of composite factors is shown in table 9.

The mission equipment package was specified by NASA, hence technology is assumed to be current. Mechanism technology levels for concept specific components such as the tiltwing mechanism, the blade fold mechanism on the tiltfold, and the rotor retraction mechanism on the variable diameter tiltrotor, are based on the most recent studies available and any weights data available. For this reason, it is believed that with moderate work, significant weight reductions could be attained as discussed in the next section.

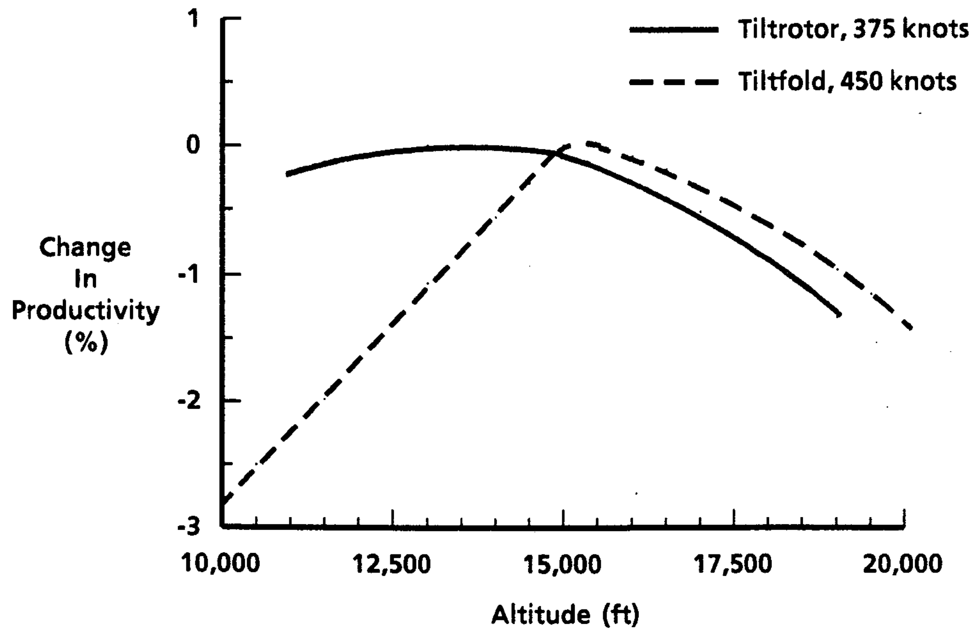

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Figure 20. Cruise altitude vs. % change in productivity.

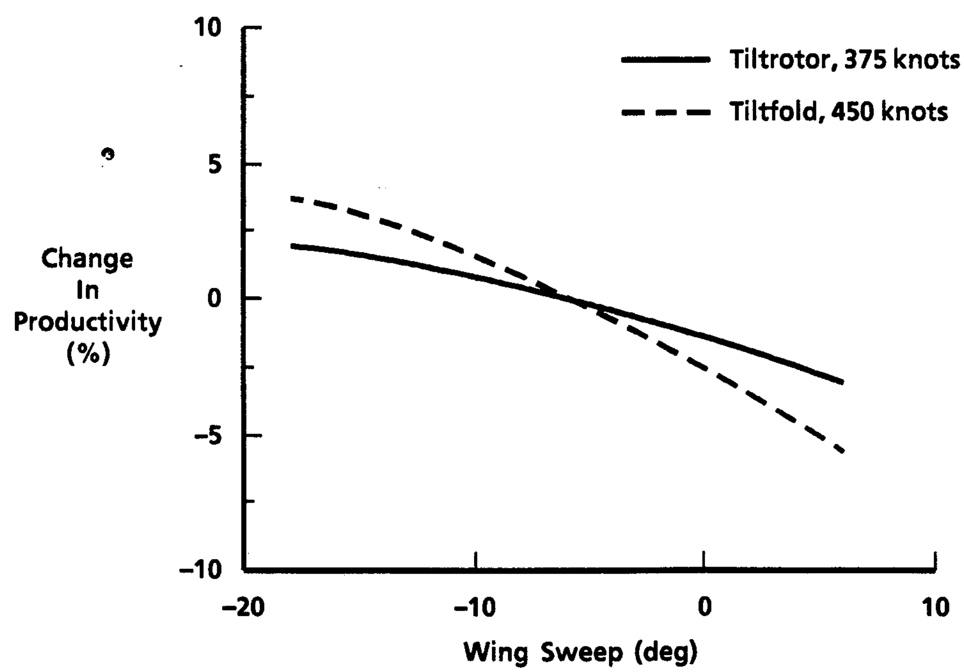

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Figure 21. Wing sweep vs. % change in productivity.

Table 9. COMPOSITE TECHNOLOGY FACTORS

Fuselage	0.74
Wing	0.81
Rotor	0.76
Spinner	0.90
Vertical Tail	0.85
Horizontal Tail	0.82
Air Induction	0.87
Nacelle	0.80
Pylon Shaft Support	0.74
Pylon Shaft	0.35
Cross Shaft - Couplings	0.99
Swashplate	0.95

Propulsive efficiency is based on V-22 rotor parameters with modified thinner tip sections. Drag is calculated using equations from Hoerner (ref. 4), with V-22 and XV-15 "check" points. Since drag is configuration dependent, it is likely that with prudent design decisions and detailed design work, the drag might be reduced, thus a technology level for cruise mode drag is difficult to assess; hence, the technology evaluation section provides sensitivity plots to indicate the range of potential drag solutions.

Aeroelastic stability and flight control technology levels primarily effect the wing weight via wing stiffness requirements. Stiffness penalties are therefore incorporated into the wing as a function of wing chord, wing aspect ratio, wing thickness ratio, and forward flight Mach numbers.

Technology Improvements and Their Impact

Breaking technology advancements down into components, four areas critical to the high speed rotorcraft lend themselves to improvement: Weights, Performance, Aeroelastic Stability, and Flight Controls. Using the three baseline configurations elaborated on in the previous section, a comparison may be made with which to assess the impact of various technologies.

Weights may be broken down into four key areas: engine weight, transmission weight, airframe and wing composite technology, and subsystem weights. Since subsystems are too numerous to consider individually, the mission equipment and the avionics packages are used as a basis with modifications applied to their combined weight. The tiltfold mechanism is broken out as another subsystem with room for improvement. The reasoning is that since the tiltfold mechanism was designed 20 years ago and since it was developed for tests with no database of large-scale loads, substantial weight savings may be achieved. Applying improvements in technology, and assessing the impact to the change in gross weight as a percentage change in gross weight, the values in table 10 are calculated.

Table 10. PERCENT REDUCTION IN GROSS WEIGHT

	450-Knot 15-Pax TF (% GW)	450-Knot 30-Pax TF (% GW)	375-Knot 30-Pax TR (% GW)
10% Reduction in engine weight	3.1	2.9	1.2
10% Reduction in transmission weight	0.9	1.2	0.8
10% Reduction in fixed equipment weight (APU, air conditioning, hydraulics, electrical, anti-ice, furnishings)	1.6	2.2	2.0
50% Reduction in blade-fold mechanism weight	3.8	4.2	-
10% Reduction in avionics weight for the equivalent functions	0.3	0.4	0.4

Taking the composite-based components with weights over 500 lb, the technology factors are modified to reflect technology improvements (see table 11). If technology were to follow a steady growth path as predicted based on historical improvements, a 6-8% improvement in tech factors could be realized. However, if all of the goals currently being pursued in various arenas of research, as discussed in the NASA-Langley funded study "Advanced Composite and Structural Concepts" (ref. 12) are achieved, significantly greater improvements might be seen. Figure 22 indicates that a potential gross weight reduction on the order of 20% might be achieved were all technology advancements accomplished.

Table 11. ADVANCED COMPOSITE TECHNOLOGY FACTORS

	Current	Anticipated
Fuselage	0.74	0.5 - 0.67
Rotor	0.76	0.7
Wing	0.81	0.5 - 0.76
Nacelle	0.80	0.7 - 0.75

Note: Technology factors represent the ratio from a metal to a composite fuselage.

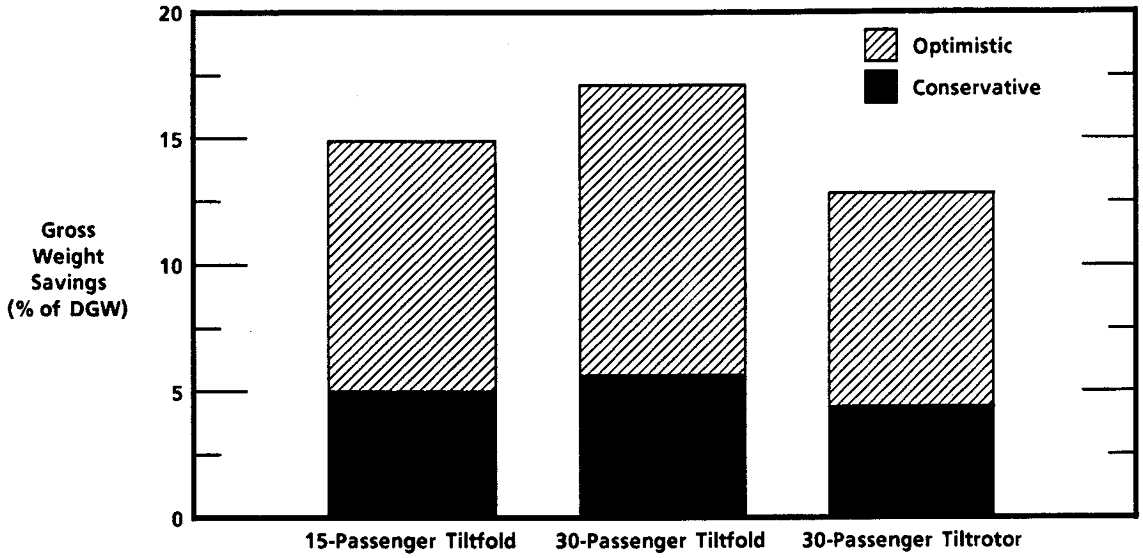

Figure 22. Percent gross weight savings due to composite improvements.

The next category for technology improvement is that of performance. It was determined that performance improvements could be realized in four major areas: offsetting the rotor Mach drag divergence (M_{dd}) effect, improving the engines specific fuel consumption, reducing aircraft drag, and reducing download. Table 12 indicates several potential areas of research that might afford the desired improvements.

Table 12. PERFORMANCE PARAMETER RESEARCH TOPICS

Offset Rotor M_{dd}	Offset compressibility effects, increase solidity, decrease tip speed, investigate spinner/propeller/nacelle interaction effects
Improve Specific Fuel Consumption	Hotter running engines, higher compression ratios
Reduce Drag	Reduce: frontal areas, wetted areas, component C_D's, interference effects, flow interaction effects, and subsonic compressibility effects
Reduce Download	Reduce: the induced velocity at the wing, the downloaded area, the flow fountain effect, and the vertical C_D of the wing

Table 13 indicates the sensitivity of each configuration designed for the speeds in table 7 to improvements in performance. It is assumed that the given percentages could be achieved through a combination of one or more of the research goals.

Table 13. PERCENT IMPROVEMENT IN PRODUCTIVITY

	450-Knot 15-Pax TF (% Improvement)	450-Knot 30-Pax TF (% Improvement)	375-Knot 30-Pax TR (% Improvement)
0.03 offset in M_{dd}	-	-	1.28*
10% Reduction in SFC **	5.25	6.18	3.69
10% Reduction in Drag	4.41	3.51	2.67
10% Reduction in Download	0.75	1.54	0.50

* At 425 knots, the same configuration would improve 4.98%.

** Engine baseline in this study is more advanced than assumed for IHPTET goals.

Figure 23 shows how the variation in equivalent drag can affect the given configurations. The combination of weight reduction and drag reduction effects is shown in figure 24.

Improving the aeroelastic stability margins can reduce the wing weight penalty for the tiltrotor. If the wing is designed by jump takeoff strength and not high speed flight stiffness, it will weigh less (as high speed flight can be a more restrictive parameter). There are several ways to improve the aeroelastic characteristics of a wing; some of them are: a focused mast/pylon, wing-tip pod center of gravity at the torsion axis, gimbaled hub and coning flexures, electronically augmented stability, and coupled mode composites. Some of these technologies, such as the gimbaled hub and coning flexures, have already been successfully employed on the V-22. Other technologies such as coupled mode composites, which effectively offset the elastic axis of the wing to coincide with the torsional axis, are quite new and in their early stages of development.

Flight control technology offers another area of potential aircraft improvement. Through control law development, the required tail volume coefficient may be reduced and rotor loads may be alleviated. It is not being suggested that an unstable aircraft be designed, rather it is now possible to design closer to the neutral stability point. A 25% reduction in tail volume coefficient would improve the aircraft productivity by 2.3% for both tiltfold aircraft and by 1.7% in the case of the tiltrotor due to weight and drag reduction. Rotor load reduction will improve maneuverability and in the case of the commercial aircraft, increase reliability (flapping angles are reduced thereby increasing the fatigue life of the component).

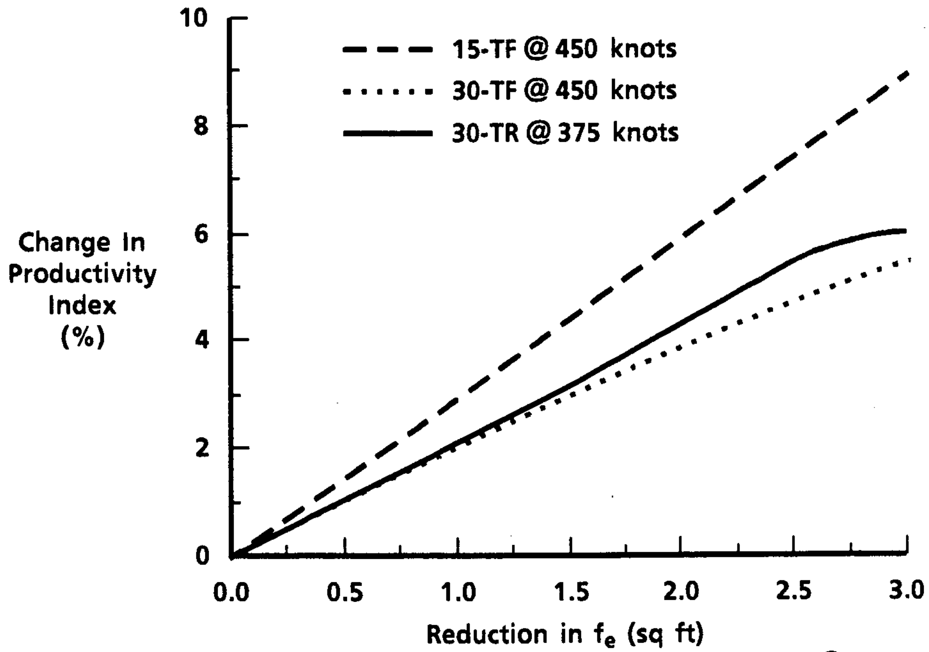

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Figure 23. Drag reduction impact.

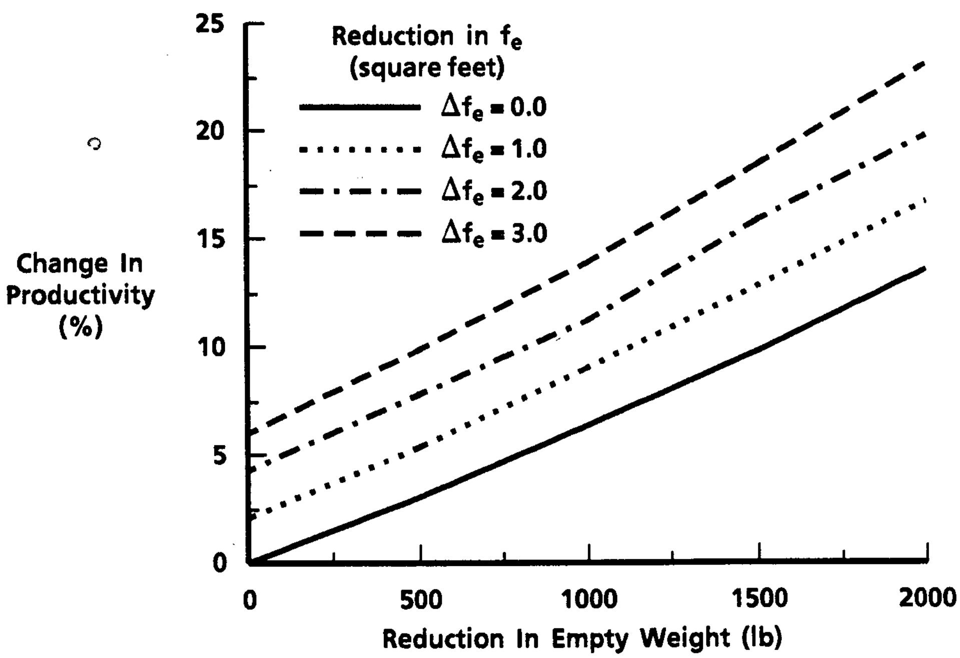

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Figure 24. Combined weight and drag reduction impact.

Combined Advanced Technology Applications

Taking all of the technology advances and applying them at once to each configuration, it is interesting to note the overall potential improvement of the various aircraft under consideration. Table 14 summarizes the assumed improvements in technology.

Table 14. ADVANCED TECHNOLOGY DESIGN ASSUMPTIONS

10% reduction in engine weight
10% reduction in transmission weight
6-8% reduction in selected composite weights
10% reduction in avionic weight
50% reduction in weight of configuration-specific components
10% reduction in fixed equipment weight
0.03 offset in rotor M_{dd}
10% reduction in specific fuel consumption
10% reduction in cruise mode drag
10% reduction in download
25% reduction in tail volume coefficient
Removal of high speed wing stiffness penalty

Looking again at the range of productivity vs. speed for each configuration, figures 26 and 27 indicate a general improvement of approximately 30% for all configurations. It may also be noticed that the general trends have remained the same; however, at the 450-knot design point, the margin of difference between configurations has reduced dramatically. In fact, both the tiltrotor and the tiltwing aircraft are now capable of attaining the 450-knot design point at nearly the same productivity as the previous 375-knot design point for the tiltrotor. The tiltwing is shown here for reference only ignoring the problem of low speed transition and shallow landing approach glide angles as mentioned previously. For this reason, only the tiltrotor and tiltfold are discussed further regarding technology tasks.

Taking the optimal configuration at 450 knots for the two tiltfold aircraft and the 30-passenger tiltrotor, and performing a partial derivative analysis where all advanced technologies but one are held constant, the five areas with the most impact may be determined. Table 15 indicates what these areas are for the tiltfold aircraft and table 16 represents those for the tiltrotor. Note that the percentages represent <u>losses</u> in productivity were that particular technology <u>not</u> applied to the fully advanced aircraft. The large improvement in productivity of the advanced, 450-knot tiltrotor due to improved rotor M_{dd} is simply based on the value of propulsive efficiency being considerably lower with current technology at 450 knots.

The changes assumed on the left-hand column of tables 15 and 16 are not to be taken as "equal difficulty" -- but rather, judged to be "doable" by year 2000. In some cases more resources may be required than others. For example, a 10% reduction in specific fuel consumption may be more easily achieved than a 0.03 offset in rotor M_{dd}. The technology

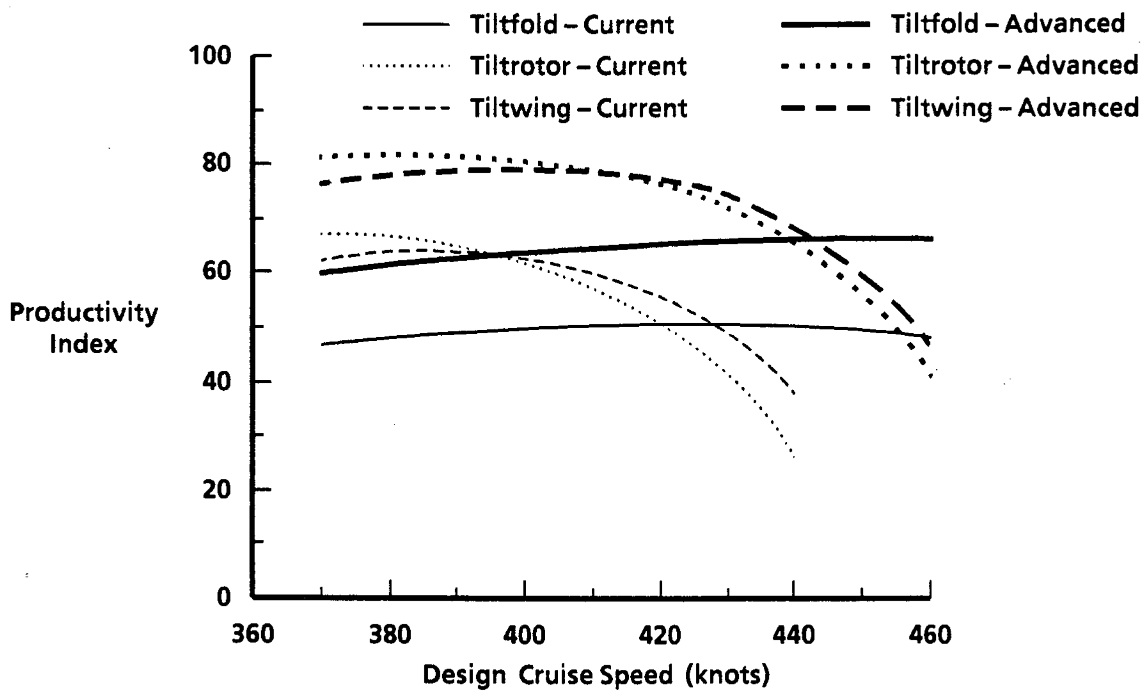

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Figure 25. Optimal 30-passenger advanced technology designs.

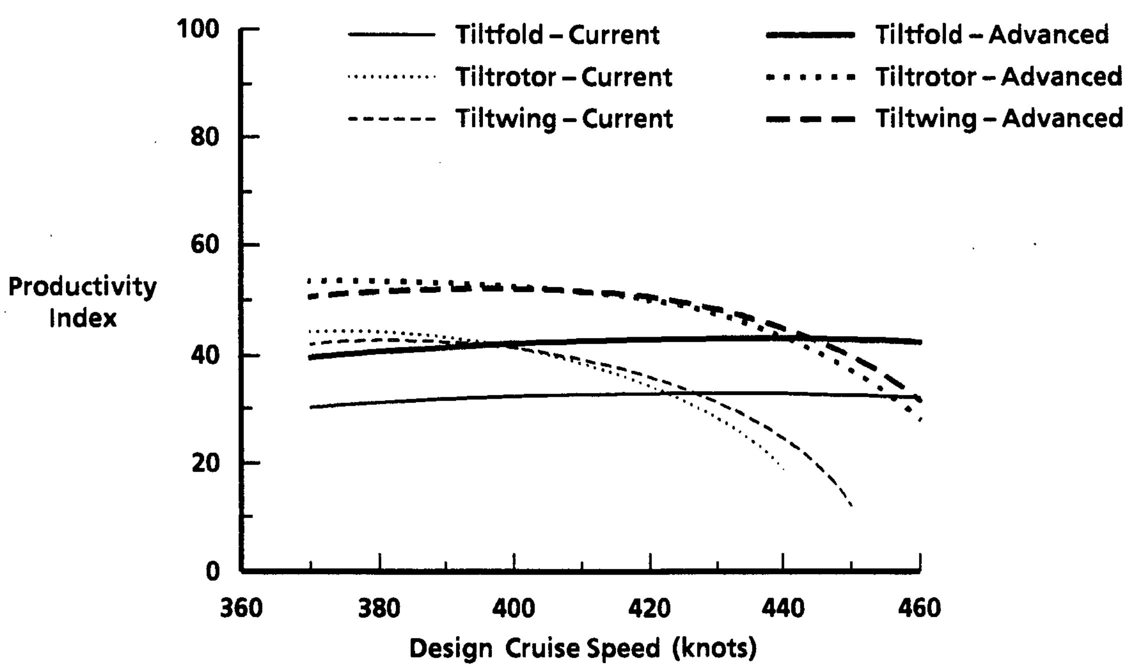

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Figure 26. Optimal 15-passenger advanced technology designs.

plans addressed in Task 3 emphasize addressing the critical technologies for productive cruise speeds of 450 knots.

Table 15. ADVANCED TILTFOLD TECHNOLOGY NEEDS, 450 KNOTS

Percent of Productivity Change if Not Done →	30-Passenger (%)	15-Passenger (%)
6-8% reduction in selected composite weights	−5.5	−5.5
10% reduction in cruise mode drag	−4.4	−4.6
10% reduction in specific fuel consumption	−4.2	−4.6
50% reduction in blade fold mechanism weight	−3.7	−3.7
10% reduction in engine weight	−2.5	−3.0

Table 16. ADVANCED TILTROTOR TECHNOLOGY NEEDS, 450 KNOTS

Percent of Productivity Change if Not Done →	30-Passenger (%)
0.03 offset in rotor M_{dd}	−59.6
Aeroelastic wing stiffness alleviation	−8.7
10% reduction in cruise mode drag	−8.2
6-8% reduction in selected composite weights	−6.3
10% reduction in specific fuel consumption	−6.2

Table 17 reviews the various technical parameters considered in, and their general affect on, this conceptual study. Emphasis was placed on variables affecting "sizing" of the aircraft investigated in Task 2 rather than generating detailed characteristic technical data for alternate missions. This approach puts a premium on defining those parameters germain to operational productivity in the design mission profile selected.

Table 17. PARAMETER GUIDE

Design criteria actually used	Fig. 1, Table 7
General arrangement drawing (current technology)	Figs. 4, 5, and 6
Rotor and wing geometry including airfoil sections, twist, taper, etc.	Table 2; Rotor: like V-22 with thin tips; Wing: like V-22 but scaled thickness (reduced)
Rotor characteristics including hub description (conceptual), equivalent hinge offset (if appropriate) and tip speeds	Like V-22, Table 7
Wetted areas and frontal areas of major components	Tables 4, 5, and 6
Weight summary by major groups per format of MIL STD 1374 - Part I	Table 3
Vehicle inertias in hover and cruise	Derived in GARP for tiltwing control fans only
Empty weight to design (VTO) gross weight ratio	Table 3
Hover and cruise mode nondimensional power and thrust	Embedded computation in GARP for sizing mission only
Hover mode download as a percentage of hover gross weight	Reference Table 7 (percentage of thrust)
Cruise mode lift-drag polars	$q\,f_e$ + induced drag in GARP
Lift coefficient of lifting surfaces in each flight mode	As required for sizing mission GARP
Cruise mode drag breakdown	Tables 4, 5, and 6
Cruise mode propulsive efficiency	Tiltrotor per GARP $\approx$ 71%; tiltfold per engine data
Power required and thrust required vs. airspeed at mission gross weight and at minimum flying weight throughout the nominal flight envelope at sea level, 10,000 ft, 20,000 ft, and 30,000 ft, if attainable, standard conditions	Derived as required in GARP to satisfy sizing mission.
Rate of climb vs. airspeed (all modes) for standard and hot day (ISA + 15°C) conditions	Tiltrotor: 3556 fpm; Tiltfold: 1321 fpm (fans) @ climb speed in mission profile
Hover ceiling out of ground effects vs. weight at standard day and hot day conditions	Figs. 7, 8, and 9
Cruise mode specific range vs. airspeed for sea level, 10,000 ft, 20,000 ft, and 30,000 ft, if attainable, standard day conditions at mission gross weight and at minimum flying weight	Derived as required in GARP to satisfy sizing mission
Payload/range characteristics. One engine inoperative (OEI) characteristics for critical mission segments of civil missions	Figs. 10, 11, and 12; OEI-capable takeoff
All engines inoperative characteristics	Figs. 7, 8, and 9 (all engines operative)
Autorotation capability if any	Flare at 50 to 80 knots touchdown
Short takeoff characteristics (e.g., useful load increase)	x 2.5 to 3.0 useful load at design gross weight
Airspeed-altitude envelope for 1g level flight, standard day, showing all limits (e.g., power, torque, control, etc.)	Basis for selection of tiltfold for 450 knots (power, torque, control limits, when applicable, embedded in GARP)

Table 17. PARAMETER GUIDE (Concluded)

Conversion envelope and limits (e.g., power, attitude, control, etc.)	Like V-22
Productivity factor (V_{cr} x PL/WE) for civil missions	PR1 Reference Table 1
Effects of cg travel on conversion envelope and trim margins	Not critical
Sideline noise at 500 ft for a hover 100 ft above ground level	Table 8
For the civil mission, ICAO flyover, approach and departure noise levels	Simulations required for steep approach limits
Downwash and horizontal sidewash from ground level to 6 ft AGL at most severe and most favorable location in the vicinity of the hovering vehicle at a wheel height of 25 ft	Like V-22
Control system concept description	Like V-22 for tiltrotor; plus fig. 13 for tiltfold
Proximity of structural stability limits to normal flight envelope	Criteria: 1.15 x 1.2 V_H; weight algorithms as required (V_H = 1.1 V_C)
Power train efficiency and loss breakdown by system element (e.g., transmission, compressor, accessories, etc.)	GARP overall losses for drive, accessories (Typical: transmission 5%; accessories 4 to 6%)
Engine characteristics, including power (thrust) available and fuel flow as a function of altitude, temperature, and airspeed	GARP scaling and lapse rates (Typical: power lapse per "Carlson" factor)
Engine inlet loss assumptions	GARP installation losses (Typical: 4%)
Auxiliary propulsion system elements (e.g., compressors, auxiliary engines, etc.), weights and fuel consumption	Per Table 3 (NASA specified)
Engine characteristics during the conversion process	Fig. 13
Maneuver capability such as turn rate, g capability, yaw rate, acceleration, etc. in hover/low speed mode; conversion and high speed mode	Criteria consistent with FAR Part XX
Discussion of costs and manufacturability considerations	Key subject of reference 12 (manufacturability) D.O.C. addressed by PR1 (see Appendix)

ENABLING TECHNOLOGY PLAN

Critical Issues Specifically Related to High Speed Rotorcraft

Issues that drive priorities for technology tasks have to do with the business of staying economically healthy in an increasingly competitive world. The gestation periods for the development of productive aircraft are longer than many industries, or nations, care to admit. This reaffirms the need to recognize high priority, short-term and parallel, high priority, low-level, longer-term activities when the growth path of development becomes evident. Completing these tasks generates the options to ramp-up to subsequent, relatively higher-cost development with low risk. If the short-term tasks are favored to the exclusion of the long-term due to the scarcity of resources, or to an erroneous perception that no better path to improved competitiveness exists, then the "competition" has a clear opportunity for eventual superiority by working on the long-term tasks. The critical issues that need to be addressed to implement the usefulness, speed, and efficiency of high speed rotorcraft with a low level of development cost and schedule risk are discussed below to serve as a focal point for the technology plan recommendations given later in this section. Subsequent discussions of related current and proposed programs identify the near- and long-term priority tasks.

"Usefulness" results in a High Speed Rotorcraft line that for commercial applications becomes and remains economically viable. It performs a service for which there is a demand by the traveling public. It lives within a society that considers it a valuable neighbor. It is a good investment for its operators . . . in this country and abroad. Typical issues to be favorably resolved to make this happen are:

a. Can the passenger save total trip time when flying by high speed rotorcraft without paying more for the total door-to-door trip than required by other modes?

b. Can the high speed rotorcraft operate from locations that are economical and convenient to the travelers' trip origins and destinations while avoiding unacceptable intrusion on the neighbor's environment (such as noise)?

c. Can the operator maintain schedule reliability while he is trying to maximize the number of fares per flight hour for a given level of direct operating cost?

"Speed" must be right for the job. The High Speed Rotorcraft designed for commercial operations will be the result of resolving two issues to determine the "right" design cruise speed. These are:

a. At what speed does the "full-cabin" productivity of any candidate aircraft peak for a given block distance?

   This addresses, for example, the maximum-capacity fare revenues per hour for a given block distance divided by the amortization and operating costs per hour of the aircraft. A related measure defined for this study is the productivity index, PR1. It is relatively simple to quantify a measure such as this in the conceptual design stages based on preliminary estimates of the parameters with assumed technology levels. But as technology development progresses, a continual audit of productivity is needed using "emerging reality." The best assessment of design speed can then be made when it comes time to harden the specification and to conduct the real tradeoffs needed to reprioritize technology tasks in keeping with available resources. For this study, 450 knots has been selected. The next paragraph indicates factors needed to harden the speed target.

b. Can a speed advantage of one rotorcraft over another favorably affect passenger demand (passenger load factor)? The "full-cabin" scenario might exist in a heavily patronized shuttle-type environment. However, a lesser demand may have to be shared between two aircraft designs. A question to be addressed is: Can the faster aircraft generate sufficiently higher passenger load factors to offset a higher direct operating cost? If it can, marketplace dynamics may see the demand for the slower aircraft drop, thereby reducing its viability. If this effect is present, it indicates that the speed goals should be faster than the speed for peak "full-cabin" productivity. The premise for this study is that this effect may justify the NASA-specified cruise speed of 450 knots. Further assessment of a "competitor's" ability to generate an increased passenger load factor by marketing quicker trips through increased speed (beyond the productivity peak), improved ride, and reduced internal noise levels while remaining economically viable is needed before a design cruise speed specification can be established responsibly. This encompasses many new parameters to describe the envisaged operational scenarios (routes, regulations, ride quality, schedule and enroute reliability, etc.). Such tradeoffs are typical of system analyses early in the conceptual design stage.

"Efficiency" at all levels of the High Speed Rotorcraft life cycle is important for economic growth. For example, the successful operation of a fleet of one aircraft having a higher direct operating cost than a fleet of another design may be offset by an austere indirect cost policy. In the following discussion, the efficiencies referred to pertain to those influenced by vehicle technology. Once an aircraft design is in service, the operator attempts to fill his seat capacity and may arrange the block distances along his available routes to maximize fares per flight hour. He has only secondary control over the weight empty and fuel flow terms in the productivity index equation. However, the technology development stage is most influential for improving weight and fuel efficiencies for any design payload and design block distance. The efficiency issue here for the High Speed Rotorcraft boils down to the approaches for optimizing the design tradeoffs between improved weight empty and fuel load in the speed range likely to be the arena for the economic contest between approaches (given that at least a minimum acceptable level of operational availability, maneuverability, service life, etc. can be assured). The work of Task 1 and Task 2 of this study has shown that, fortunately, this can be addressed by a continuity of rotorcraft technology; the tiltrotor and the tiltfold rotor. The summary issue statements are:

a. How much can the weight and performance efficiency of the tiltrotor be extended to improve the speed for peak productivity without compromising component service life, mid-speed maneuver capability, and aeroelastic stability speed margins?

b. At what design cruise speed does the tiltfold become lighter than the tiltrotor for a given design mission? At speeds lower than the crossover point, the fuel efficiency of the tiltrotor generates a fuel load plus weight empty that is clearly lighter than that with the tiltfold propulsive fans and fold system. However, above that speed, the decay of tiltrotor propeller efficiency due to the onset of compressibility effects creates a rapid increase in fuel load and a situation that results in the tiltrotor becoming the heavier gross weight solution. Just where the crossover occurs requires that the weight estimates of the rotor fold system required for the stop-fold conversion sequence be validated for realistic gust load and maneuver design criteria that would exist at conversion speeds. In addition, it requires that the weight of the convertible fan-shaft engine power transfer coupler be validated.

It is not obvious that resolution of the demand issue (b. under "Speed" above) for civil applications will preclude the tiltfold. In military missions, the option to use superior speed capability has been axiomatic for tactical superiority providing that mid-speed maneuverability is not compromised.

Several of the issues described above are being addressed by current and planned Government programs. These are discussed in the next paragraph.

Current and Anticipated Programs that Benefit the High Speed Rotorcraft

The programs discussed are in the areas of propulsion, aerodynamics, structures, control laws/simulations, and flight research.

Propulsion- Two ongoing programs are important to the High Speed Rotorcraft activity; their sensitivities are given in tables 15 and 16. These are the Integrated High Performance Turbine Engine Technology (IHPTET) program and the Advanced Rotorcraft Transmission (ART) program. Both programs deal with several contractors and are monitored through NASA Lewis. Both are considered generally applicable to high speed rotorcraft in that they reduce engine and rotor transmission weight and reduce fuel flow through engine and transmission efficiency improvements. Goals for improvement in those programs run from 25 to 50%. These percent improvements are greater than assumed in this study because "current" technology herein is assumed to be more advanced.

The Precursor Convertible Engine Studies with Allison and General Electric are examining turboshaft engines with technology improvements in the 8000 hp class. These are applicable to advanced tiltrotor configurations. In addition, separate means for powering lifting rotors and forward propulsion are being examined and include the means for powering the tiltfold system. These benefits are considered important to long-term results addressing the efficiency issues.

The ART program includes transmission technology features which not only would benefit tiltrotor and tiltfold concepts but also other shaft-driven rotorcraft. These benefits are considered important for achieving long-term results addressing the efficiency issues.

Aerodynamics- An important anticipated program is the 1/4-scale V-22 full-span acoustic tiltrotor model that was announced in the Commerce Business Daily. Tests will be conducted in at least two tunnels, with configuration modifications to allow validation of methods for predicting and controlling noise levels in the terminal areas. This program is considered important for complementing near-term results applicable to the Civil Tilt Rotor program. (See Flight Program below.)

Structures- As an outgrowth of a Bell-NASA Langley contract on composite fuselage structural concepts for reducing weight and cost, a next phase involving full-scale major test components is expected for validating design and manufacturing methods. Critical components that are major contributors to reduced weight cost and drag include the wing and the wing-fuselage junction for a Civil Tilt Rotor size vehicle. Additionally, the design of pressurized composite transport fuselages presents a challenge that has been identified as an excellent opportunity for major weight and cost reduction development. Results from this area of technology development are common to high-speed rotorcraft applications and can be considered long-term.

Control Law, Advanced Cockpit, and Simulation- The location of vertiports will be a key factor for determining the economic viability of the entire air transportation system in the future. The reduction of air traffic congestion at airports will mean a more productive jet transport system. Congestion can be reduced by offloading jet runways of smaller feeder aircraft. This is done through a greater reliance on vertiports. Vertiports will work given that they reduce the traveler's ground travel time by being closer to trip origins and destinations and intermodal links. Close-in locations imply nearby population zones with corridors aligned to clear areas. Greater selection of corridors will be possible when steep approaches are used to minimize the exposure of populated areas to approach and departure noise. A key to utilizing the inherent steep approach capabilities of the tiltrotor or tiltfold in the terminal areas will be the specific cockpit and air traffic control procedures developed by ongoing developments in control law, advanced cockpit and simulation technologies. The Terminal and Enroute Procedures (TERPS) investigations by the FAA for advanced rotorcraft will be a high-priority, near-term, result-oriented program that will generate data usable for VTOL cockpit optimization and air traffic controllers alike.

Flight Program- The use of advanced rotorcraft for civil applications requires an operational proof of concept rather than a technical one. The best way to prove the "usefulness" of this new system is to use it. The Civil Tilt Rotor study has shown that an infrastructure demonstration is needed to address municipal concerns in location of vertiports, traffic control concerns about procedures, technological improvements to improve operational options, and operator concerns over schedule reliability. This program is considered to be high priority for near-term results because the infrastructure must be defined and workable in order for high speed rotorcraft to have a future.

New Technology Tasks for High Speed Rotorcraft

There are specific, critical tasks not addressed by the programs described above that are considered to be prerequisites for realizing the High Speed Rotorcraft goal of 40 knots. The plans for these tasks are described in this section.

The 1989 Long-Range Program Plan published by NASA defines two tiers of activity for High Speed Rotorcraft: a preliminary activity that covers from the present to approximately calendar year 1994; and, a possible new initiative starting from about that year wherein acceleration to more intensive levels of activity would be expected. The tasks that fit the "new initiative" time frame can be considered to include specific HSRC flight research and piloted simulations based on the work done during the current preliminary phase. This section describes those tasks more appropriate to the current phase. These types of tasks include development of analytical codes, critical structural component tests, and wind tunnel tests.

Within this category may be placed those tasks that are common to any HSRC vehicle concept and those that are concept-specific. The "common" tasks are principally the "long-term" tasks described above under discussions of current and anticipated programs but with one addition. This section concentrates on the concept-specific tasks believed to be critical and includes the additional task common to the HSRC missions.

The missions investigated in this contracted activity are the the civil transport aimed at 450-knot cruise speed capability. However, the concept-specific tasks defined below are designed to be robust enough to improve the productivity of the tiltrotor and tiltfold over a broad range of cruise speeds so as to address the issue of identifying the productivity crossover speed between the two. The "additional" common HSRC task is aimed at assessing all principal and alternate applications of the emerging high speed tiltrotor and tiltfold technology results for defining mission speed specifications based on both productivity and demand incentives.

Concept-Specific HSRC Tasks-

1. The High-Speed Total Envelope Proprotor (HI-STEP) Program

Objective: Demonstrate that a sub-scale aeroelastic model proprotor based on a design that has sufficient strength and rigidity to satisfy low airplane speed maneuver and gust loads, and to satisfy wing/pylon/proprotor aeroelastic stability margins for 450-knot cruise Mach numbers, can provide competitive cruise propulsive efficiencies and satisfactory hover performance and hover control moments.

Approach:

Prototype – The 30-passenger, 450-knot cruise speed, advanced technology tiltrotor point design will be selected as the reference prototype. This design uses 38.6-ft diameter rotors and a hover tip speed of 780 fps.

Scaling – Its proprotor will be scaled to preserve Lock, Mach, and Froude number in freon at reduced pressure to achieve the same density as air (i.e., 1/5th-diameter scale; approximately 7.7-ft diameter proprotor) and to operate at scaled hub horsepower and rpm overspeed ratings.

Model Design and Build – Proprotor airfoil, twist, and chord distributions will be optimized based on aerodynamic, dynamic, structural and manufacturing factors to achieve competitive propulsive efficiencies at the design cruise Mach numbers while having strength and stiffness needed for maneuver and gust loads and aeroelastic stability criteria. Two-dimensional (2-D) models of selected airfoil sections will be prepared for wind tunnel tests. Tailored-mode composite model blade and wing specimens will be designed and prepared for laboratory tests. Servo controls that include instrumented and remotely controlled cyclic and collective pitch will be provided. The proprotor will be aeroelastically scaled and strain gaged to monitor loads. Rotor model instrumentation will be included to measure rotor thrust, torque, and trim conditions. Spinner system static pressures will be measured. An aeroelastic, scaled, semispan wing assembly will be designed to hold the rotor and pylon in an unpowered configuration for proprotor aeroelastic stability boundary tests. A shaker system will be included for exciting the principal modes for modal damping assessment. Control system algorithms for augmenting stability if necessary will be devised. Load cells, if needed for the propulsive efficiency determinations, that could interfere with stiffness distributions of the aeroelastic test configuration will be removable or isolated for stability boundary investigations. A drive system (transmission and motor system) will be provided to achieve the high speed power envelope in a powered "propeller stand" configuration using the same proprotor hardware.

Model Calibration and Tests –

a. 2-D airfoil tests will be conducted in a commercial wind tunnel to validate the predicted airfoil characteristics.

b. Tailored-mode composite model blade and wing specimens will be tested to validate structural properties.

c. Model component sensors will be calibrated for the planned test range.

d. The assembled, unpowered, semispan aeroelastic model will be calibrated and functionally checked out prior to each aeroelastic test.

e. A preliminary and a principal aeroelastic data test entry in the Government-provided transonic dynamic tunnel (TDT) is planned.

f. The assembled, powered, propeller stand model will be calibrated and functionally checked out prior to each test.

g. A hover efficiency and control moment data test will be conducted in air at sub-scale Mach numbers.

h. The model will be installed in the Government-provided TDT for preliminary system check out in air and freon. Subsequent tunnel entries for propulsive efficiency data in freon will be conducted up to maximum model speed.

Reports –

a. A test plan, a safety report, and a data report will be prepared for each wind tunnel facility test

b. A final assessment report will be prepared showing the aeroelastic boundaries and propulsive efficiency envelopes predicted and demonstrated for the cruise configuration. Predicted and tested hover data at sub-scale Mach numbers will be included for the static performance condition. Critical component structural loads will be presented. The control settings for trim and dynamic conditions will be shown. The specific analytic codes used for predictions will be identified by name and version. Specific new codes generated to reconcile predicted and test data will be referenced by name only if proprietary. Qualitative comments on the powered and unpowered model behavior will be summarized.

Resources: The program is based on a period of performance of approximately four years. The Government provides the use of the TDT and normal operating and maintenance personnel, model and systems electrical power source, and any data reduced from the tunnel monitoring and data acquisition systems. The contractor provides the model design, test hardware, models and model instrumentation, test and engineering personnel, commercial 2-D tunnel rental, and reports. Approximate value: 10-15 million ($'90).

2. Tilt Fold System (TFS) Program

Objective: Validate rotor and control load predictions for a large-scale (25-ft diameter rotor) semispan model of the tilt fold system based on a design that:

a. has sufficient strength, rigidity, and blade pitch control travel to satisfy helicopter-mode autorotation and airplane-mode low speed maneuver and gust loads

b. can execute the unpowered reversible stop-fold process at speeds and angles of attack representing the conversion envelope

c. can perform helicopter-mode autorotation in the wind tunnel

d. can provide hover efficiency data from powered whirl tests.

Approach:

Prototype – The 30-passenger, 450-knot cruise speed, advanced technology tiltfold point design will be selected as the reference prototype. This design uses 41.2-ft diameter folding rotors and a hover tip speed of 780 fps.

Scaling – The proprotor will be scaled to preserve Lock and Froude number in air. The Mach scale will be no less than the square root of (25/41.2) or .7788. This results in a design hover tip speed of not less than 607 fps and a (full aircraft) design gross weight of not less than 9500 lb.

Model Design and Build – The tiltfold model wind tunnel test can be carried out entirely without rotor power since all powered operations in the conversion speed range have been demonstrated by normal tiltrotor flight operations. The rotor will, however, be capable of powered testing on a whirl rig. A semispan wing-pylon-rotor and controls assembly will be aeroelastically scaled to permit pylon tilt over a range of approximately 100 degrees and "inflight" blade stop-fold transitions (and reverse). The design test envelope will include the scaled conversion corridor of speed (plus aeroelastic margins) and the related maneuver angle of attack range in the conversion corridor in airplane mode. Helicopter mode pylon tilt angles will permit rotor autorotation over the expected range of wing angles of attack in that mode. The model will include wing, flaperons, rotor, spinner, fairings, blade cuffs, folded blade retention devices and the mechanisms, actuators, and instrumentation to acquire the loads data in the test envelope. Aerodynamic exciter vanes will be included for checking damping of the structural modes of the wing-pylon system. The principal differences between this model and the model tested in 1972 are that: 1) lessons learned will be incorporated; 2) an extended feather blade pitch range will be added to the normal helicopter-mode cyclic and collective pitch range; and 3) modern mechanisms, controls, actuators, instrumentation and blade composite construction will be used.

Model Calibration and Tests –

a. Instrumented components will be calibrated and the overall model test system will be functionally tested and calibrated at the contractor's facility.

b. After shipment to the National Full-Scale Aerodynamics Complex (NFAC), the model will be built up in the high-bay area and model systems will be functionally checked.

c. The rotor will be mounted on the Outdoor Aerodynamic Research Facility (OARF) for hover performance assessment including overspeed rpm. The semispan wing will be separately mounted in the rotor wake to assess download at various pylon tilt and flaperon settings with the low twist, tiltfold blades.

d. Upon wind tunnel entry, calibration loadings will correlate model and tunnel balance instrumentation data.

e. Wind tunnel tests will be conducted to acquire loads and control requirements over the zero-torque operating ranges in the helicopter autorotation range and in the airplane stop-fold transition range.

Reports –

a. A test plan report, a safety report, and a data report will be prepared for each test at the NFAC.

b. A final assessment report will be prepared showing the loads, dynamic response, performance and control requirements for various quasistatic conditions during the stop-fold process as well as continuous stop-fold processes and reversals. The variation of forces and moments as a function of the quickness of transition will be assessed as to the affect on the aircraft. The loads, performance, and control for operation in helicopter autorotation and hover will be summarized and assessed.

Resource: The program is based on a period of performance of approximately four years. The Government provides the use of the NFAC and normal operating and maintenance personnel, model and systems electrical power source, and data reduced from the tunnel monitoring and data acquisition systems. The contractor provides the model design, test hardware, models, and model instrumentation, engineering and test personnel, and reports. Approximate value: 12-17 million ($'90).

HSRC-Common Tasks-

HSRC System Evaluation: This task provides ongoing operational and system performance requirements tradeoffs, configuration control for contending vehicle concepts during the technology development stage, assessments of mission productivity and user demands based on emerging technology results and recommends areas for redirection, if necessary, of technology development to achieve the most competitive HSRC specification. Methodology development for modeling the physical and operational systems under evaluation is ongoing and audit trails are fully documented. A minimum three-man level of effort is maintained during the HSRC technology development period. Semiannual status reports and briefings disseminate results.

Other HSRC-Common Tasks: HSRC-Common tasks are coincident with those given under Current and Anticipated Programs above in the category of long-term tasks under propulsion and structures. (The HSRC-Specific tasks described previously focus subtasks in the areas of aerodynamics, dynamics and control laws technology toward specific test objectives yet contribute to a general HSRC-Common technology base.)

In addition, HSRC-Common tasks include the propulsion area. Specifically, the Precursor Convertible Engine program is aimed at advancing turboshaft core engine specific weight and specific fuel consumption in the 8000-hp class; highly appropriate for a productive HSRC tiltrotor designed for about 375- to 385-knot cruise speed. Additionally, a specific need considered critical for the TFS is the high specific power coupler for a simple, fixed-pitch fan optimized for high speed cruise. This would complete a key component for convertible engine capability that could have application to high speed rotorcraft alternatives in that fan noise and thrust would not be a concern for terminal area operations. A subscale power class for the fan coupler "matched" with the large-scale, TFS 25-ft model described above would be rated at approximately 1400 hp. It should be noted that this would be maximum power at coupling at approximately 80 percent N_2 and not the full, locked-up, dash-speed power capability of the related fan.

CONCLUSIONS

The conclusions under this contract are summarized as follows:

Near-term tasks that have been identified under this study are also compatible with some defined under the Civil Tilt Rotor program principally to answer questions related to "usefulness." Not all questions are in the domain of NASA's activity but those regarding ways of reducing noise and some operational procedures may be addressed. These include current and anticipated wind tunnel tests to validate noise prediction techniques and explore key tiltrotor design parameters, and through steep approach tiltrotor flight simulations to develop the basis for minimum-footprint vertiport land requirements and related terminal area procedures.

Long-term tasks are the preliminary, low-level, critical technology activity prior to the ramp-up to new initiatives for HSRC. The recommended tasks following are summarized under HSRC-Specific and HSRC-Common programs.

HSRC-Specific Programs

These new technology programs are identified as critical for the 450-knot rotorcraft:

HI-STEP, High-Speed Total Envelope Proprotor- Demonstrate tiltrotor cruise to 450-knot proprotor Mach numbers with a 1/5th scale model rotor designed to achieve competitive cruise propulsive efficiencies and meet low-speed maneuverability and gust load strength, and high-speed aeroelastic stability criteria.

TFS, Tiltfold System- Validate the design methodology and performance predictions for the tiltfold process by wind tunnel tests of a large-scale (25-ft diameter) tiltfold rotor system. Confirmation of loads during the stop-fold process will be a key factor in prediction of flight system weights.

HSRC-Common Programs

HSRC System Evaluations- Provides baseline "configuration control" for contending HSRC vehicle alternatives. Establishes methodology for conducting tradeoffs of air vehicle characteristics evolution based on emerging technology developments. Evaluates effects of mission and operational requirements on HSRC specifications for most competitive configuration and component development tasks.

Other HSRC-Common Programs- Current and anticipated programs depend on IHPTET including the Precursor Convertible Engine program; ART; low cost, light weight composite structures and pressurization; rotor noise aerodynamic investigations; and terminal area procedures simulations.

Tasks that would be addressed under a subsequent "HSRC New Initiatives" program are in the areas of flight research and flight simulations resulting from the tasks defined above.

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APPENDIX

Technology Needs for High Speed Rotorcraft

Task 1 Interim Report

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SUMMARY

The results by Bell Helicopter Textron, Inc. (BHTI) of Task 1, Contract NAS2-13072, are presented in this interim report. The spectrum of vertical takeoff/landing (VTOL) aircraft concepts from the pure helicopter to the Harrier-type lift jet is examined for concepts suitable for the cruise speed range of 350 to 500 knots in combination with the capability for hover at mission takeoff with one engine inoperative (OEI). The purpose of the investigation is to identify key technology areas to assure that the concepts can be applied to civilian and military missions with low risk.

A generalized measure of efficiency is defined which can be applied to military or civil missions in the conceptual design stage. Parameters include: payload, range, time, passenger load factor, weight empty, fuel, survivability, and availability. The NASA-defined, 600 nautical mile (n.mi.), civil transport missions at 15- and 30-passenger size are selected for study and the measure of efficiency is tailored and simplified for that use. This measure is called the productivity index, PR1. Qualitative assessments are also used in the evaluation of concepts. These are aimed at the parameters in the generalized measure which are not quantified at this stage of conceptual design.

The concepts examined in Task 1 are: the tiltrotor, the variable diameter tiltrotor, the tiltwing, and the tiltfold variant of the tiltrotor. In the speed range from 350 to 500 knots, the 30-passenger version of the tiltrotor is found to reach the highest productivity index of the four types analyzed herein. Its peak productivity cruise speed is 375 knots; approximately 100 knots faster than the cruise speed of the V-22. Based on "current" technology aircraft predesign (PFRT engines in 1995), only the tiltfold concept is productive at the NASA-defined mission cruise speed of 450 knots. Efficiencies of the propeller aircraft drop off rapidly as 450 knots is approached. Fuel weight requirements rise to more than the fold system weight plus fuel in the tiltfold concept. The merits and problems of each type are discussed.

Improved productivity is obtained by advancing concept-specific technology for: rotor-propeller cruise efficiency, the tiltfold system, wing structural and control law developments to insure aeroelastic stability margins, and convertible engine fan coupling systems. Advanced general technology includes engine specific fuel consumption (SFC) and weight, transmissions, thick wing drag divergence delay, and reduced cost techniques for pressurized composite fuselages.

The recommended mission-concept combinations for Task 2 studies are the 450-knot tiltfold at 15 and 30 passengers and the 375-knot, 30-passenger tiltrotor.

INTRODUCTION

Producing more military effect or civil revenue per flight hour has been the incentive for increasing aircraft speeds. In this study, the goal is 450 knots for rotorcraft that can hover efficiently. The VTOL spectrum from the pure helicopter to jet lift aircraft is considered in this investigation with the objective of describing those technologies needed for the vertical-lift concepts best suited for the cruise speed range of 350 to 500 knots. The mission profile options defined by NASA in the statement of work (SOW) cover civil and military applications. Both applications employ helicopter-like, OEI, hover capability at mission start from civil terminal areas or military forward area bases. This vertical capability at mission start insures good low-speed maneuver capability throughout the mission profile during military operations. The civil application requires OEI takeoff capability to insure Category A flight safety. Alternate, rather than the design mission, operations can then take advantage of short takeoff/landing (STOL) over-load capability. Whether the aircraft are defined for civil or military use, mid-mission hover hoist rescue capability could be called upon regardless of the design mission.

Specifying a power match between cruise speeds of 350 to 500 knots and hover at takeoff with all engines operative will allow high disk loading types into contention – it is in fact this match that originally was the basis for spawning the high disk loading VTOL concepts in the 50's. Improvements in power plant specific weight and fuel consumption are just now, in the 90's, getting to the point where the low-disk loading types can enter the arena of practical hover operations with one engine inoperative. It is this arena, with a goal of 450 knots, where the High Speed Rotorcraft Technology program is focused.

The basic questions addressed by this investigation are aimed at assessing the general and the concept-specific technology needed. For Task 1, Bell has selected the civil mission categories in the 350- to 500-knot range. The aircraft types that are best in this speed range with the current level of technology will become more productive, operationally, as technology that they can use is advanced. A question that is addressed is: At what cruise speed does productivity peak? The case for speeds higher than this then depends on operator/customer demands and preferences. The assumption has been made for this study that the demand will be there and that the simplest way to satisfy productively that demand is sought.

The technology tasks can be divided into two categories: general technology that helps all contenders, and concept-specific.

The safe step is to allocate limited resources only to those tasks that can improve all contenders. However, the most productive steps will be aimed at those unusual technology tasks that are concept-specific and move to a new plateau of growth and operational capability.

An easily understood and representative definition of a measure of operational efficiency is important in this process so that comparisons can be made. No single measure suffices for all possible applications – but most measures are rooted in doing the job the quickest way for the least cost. The conclusion as to which aircraft concept is best for a particular speed range is not likely to be clearly overturned by using similar measures. It is important, however, to define representative measures.

In this study, the capability of all conceptual point designs are converged to the design conditions. Support systems and design standards are equivalent. Therefore, mission-effectiveness evaluation criteria based on payload, range, and time are essentially equivalent for all candidates designed for a given cruise speed. Evaluations of direct operating cost are beyond the scope of this study, but measures reflecting cost such as weight and fuel can be evaluated and are discussed in the development of the productivity index. Remaining are more qualitative measures such as terminal area friendliness, ride comfort, noise levels, appearance, etc. These factors are considered in arriving at the technology tasks recommended.

The definition of Bell-defined measures of efficiency is the first order of business in this report and serves to flag the relationships among the candidates that are to be observed.

BELL-DEFINED MEASURES OF EFFICIENCY

The Basis for Measures Defined

The root of the Bell-defined measures of efficiency used for the tradeoff studies in Task 1 is mission effectiveness divided by system acquisition cost and cost of ownership. In the conceptual stages, parameters that are used in the parametric performance tradeoff studies that drive, or most nearly represent, mission effectiveness, acquisition cost and cost of ownership are combined to represent measures of efficiency (cost-effectiveness). In the civil arena, this approach leads to a measure of the ability of the design to generate revenue divided by its direct expense.

Mission Effectiveness

Typically, inherent mission effectiveness for military or civilian missions are referenced to a specified payload and a characteristic range. The premium, therefore, is on getting the job done in the shortest time, and so, it measures the response time or block time required to cover the distance. Basically, higher speed aircraft satisfy this need; a higher cruise speed means (generally) a higher mission effectiveness. But higher speed generally costs more, and this must be considered in the final measure of efficiency to determine if it's worth it.

System Costs

The cost of acquisition and ownership includes some cost elements that are essentially independent of vehicle type, the indirect costs, and those influenced by contending vehicle types. In the system life cycle, the nonrecurring portions of the acquisition cost are influenced by system complexity, concept maturity, and somewhat by size. The recurring costs are influenced by size, complexity, and quantity. The operational costs are influenced by size, maintenance needs, and flight efficiency. Given that the potential quantity is the same for any vehicle contender and that complexity is measured by weight empty (or by qualitative assessments if weight is not representative) then weight empty and fuel load in the design mission are powerful parameters that relate to the overall measures of efficiency.

Other factors enter the picture that may increase costs. For instance, in the military arena, poor survivability characteristics will reduce the number in the fleet unless these are replenished to sustain a required force level. A similar effect exists if vehicle operational availability is poor; whether civil or military. In the civilian arena, a reduced passenger load factor may mean that the designed payload is not being realized and so the aircraft is oversized for the job. A smaller aircraft which will have a lower inherent productivity due to scale may be an economically better choice by having a better passenger load factor.

Measure of Efficiency - General Productivity Index

Cost-effectiveness models that are sensitive to more parameters than used in the early conceptual design stages are not warranted. But the ones that are used do need to be responsive to the mission application. Based on the discussion in the previous paragraphs, a general expression for a measure of efficiency, or productivity, which is capable of being tailored to the elements of this study is defined as follows:

$$PR = [\, P \times L \times (D/T) \,] / [\, (WE + F) \times 1/S \times 1/A \,]$$

where:
- PR = Productivity Index, n.mi./hour (hr)
- A = Availability Factor (1.0 max.), non-dimensional
- D = Mission distance, n.mi.
- F = Mission fuel (incl. reserves), pound (lb)
- L = Passenger Load Factor (1.0 max.), nd
- P = Payload (weight), lb
- S = Survivability Factor (1.0 max.), nd
- T = Time to perform mission profile (engine-on time), hr
- WE = Aircraft weight empty, lb

Some of the above factors may be unimportant for specific applications and so specific measures of efficiency may be tailored from the general one given above.

Tailoring

The above expression may be tailored to suit the type of application considered by representing the influence of each term with exponents and constants as follows:

$$PR = [\, P^a \times L^b \times (\, D^c / T^d \,) \,] / [\, (\, k1 \times WE + k2 \times F \,) \times 1/S^e \times 1/A^f \,]$$

The exponents may be used in binary fashion for simply reducing the influence of any term from its stated value to the value 1.0. The constant k1 is a weighting term that has its origins in airframe cost per pound. k2 is based on fuel cost per pound and number of trips. k1 and k2 may cover other multipliers that relate to these parameters.

Examples of tailoring are as follows:

Scenario #1

Military environment; several payload alternatives; variable mission profiles; mission time important; procurement cost a driver; utilization rates low (compared to civil applications); survivability and availability not to be quantified.

Use the following values:

a,c,d,k1 = 1.0; b,k2,e,f = 0. Therefore,

PR = [P x (D/T)] / [WE]

Scenario #2

Civil environment; payload alternatives considered; variable mission profiles (e.g., different design cruise speeds, blocks); mission time important; procurement and fuel costs important (i.e., evaluate early in life cycle when number of trips yields fuel-related costs of the same order as initial aircraft cost); availability assumed to be adequate and not to be quantified.

Use the following values:

a,c,d,k1,k2 = 1.0; b,e,f = 0. Therefore,

PR = [P x (D/T)] / [WE + F]

Scenario #3

Civil environment; same as Scenario #2 except that due to different size classes being considered for civil mission, the passenger load factor is introduced for subsequent demand investigations.

Use the following:

a,b,c,d,k1,k2 = 1.0; e,f = 0. Therefore,

PR = [P x L x (D/T)] / [WE + F]

Selected Missions and the Related Productivity Index

The missions selected for the Task 1 investigation are the civil transport ones for sorting out the aircraft types. Within the scope of the analyses appropriate to this study, aircraft types that are productive for civil missions should be productive for military uses. This means that military needs can then be satisfied by types that will eventually be productive in the civil arena. Both size classes, 30- and 15-passenger, are evaluated.

Scenario #2 productivity expression is selected and is called "PR1" herein. Tabulated data for each point design synthesized in Task 1 were submitted (refs. A-1 and A-2). Sufficient data were tabulated to reconstitute the point designs and to see elements of the productivity expression.

On this basis, the ratio of values of PR1 for the smaller size to the larger size aircraft sheds light on the passenger load factor that needs to be exceeded by the larger aircraft to be economically superior to the smaller aircraft given a finite passenger demand. At that point, the expression of Scenario #3 would yield equal values. Because the passenger load factor is not the main point of this investigation, that term is inactive in PR1 and in effect is assumed to be constant at a value of 1.0 (i.e., full cabin in all cases).

CONCEPT SELECTION FOR TASK 1

The VTOL Spectrum

The general spectrum plots shown in figures A-1 and A-2 pretty much span the options for VTOL concepts today. Since that chart was first published in the early 70's much research has taken place to bring the concepts into confrontation with reality. To these types have been added the variable diameter and stopped rotor concepts. The circulation control rotor types represented by the X-wing concept (fig. A-3) have gone through many years of study culminating in tests on the Rotorcraft Systems Research Aircraft (RSRA). The tiltfold rotor (fig. A-4) has undergone initial aeroelastic wind tunnel tests in small and large scale. New starts have been made in the tiltwing area. The Harrier is now out there satisfying the minimum response-time mission. The tiltrotor is flying in two size classes with the XV-15 and the V-22 aircraft. Figures A-1 and A-2 show the relationship between hover efficiency and speed capability when all the engine power is used for both modes of flight. If hover with one engine inoperative is an important criterion, then the curve must shift toward lower disk loadings at any given speed. This incurs an engine weight penalty from the hover perspective or a vertical lift system penalty from the cruise perspective. The problem is to find the vehicle combination that accomplishes this while providing productive useful loads for the customer's needs. Then the related technology needs can be defined. The payoff can be safer, effective, high speed rotorcraft for military and civil use.

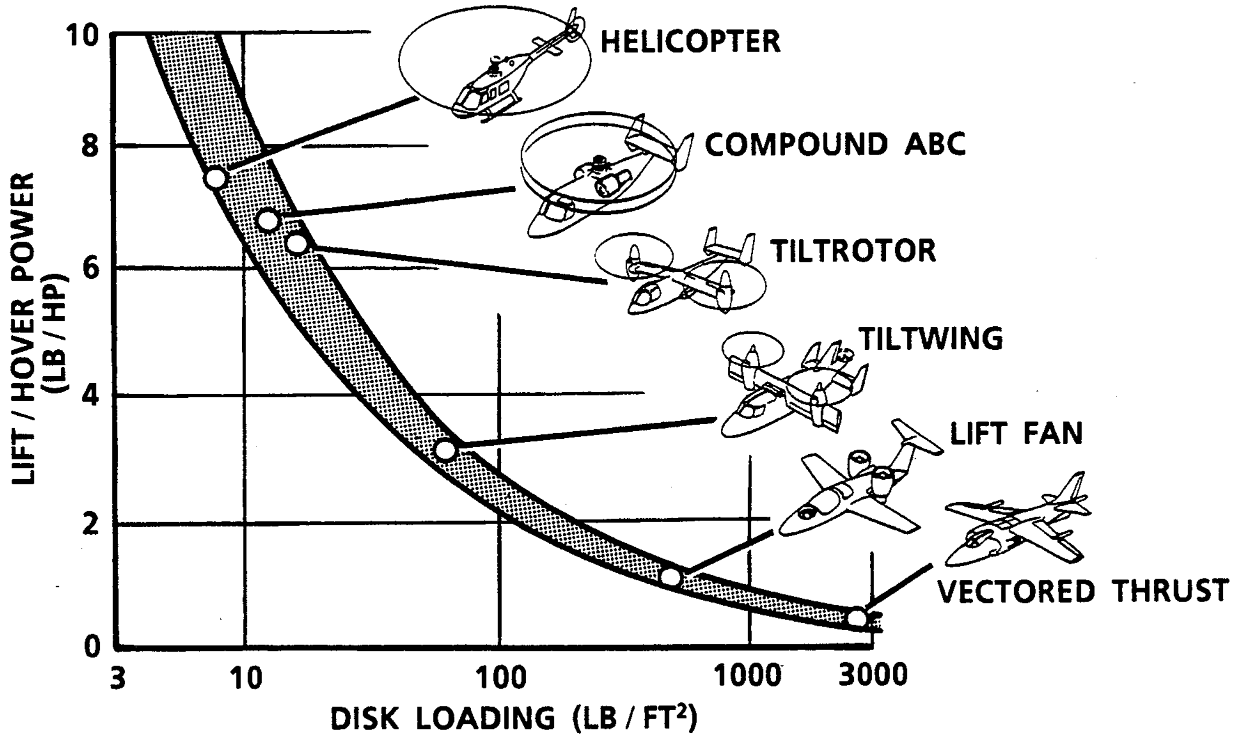

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Figure A-1. Disk loading spectrum.

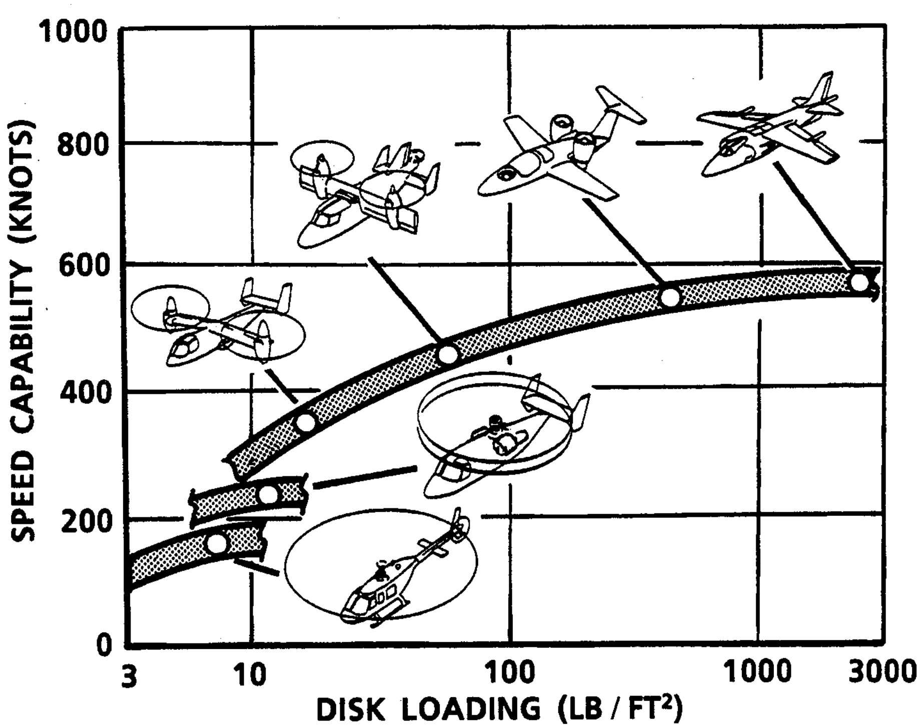

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Figure A-2. V/STOL speed capability.

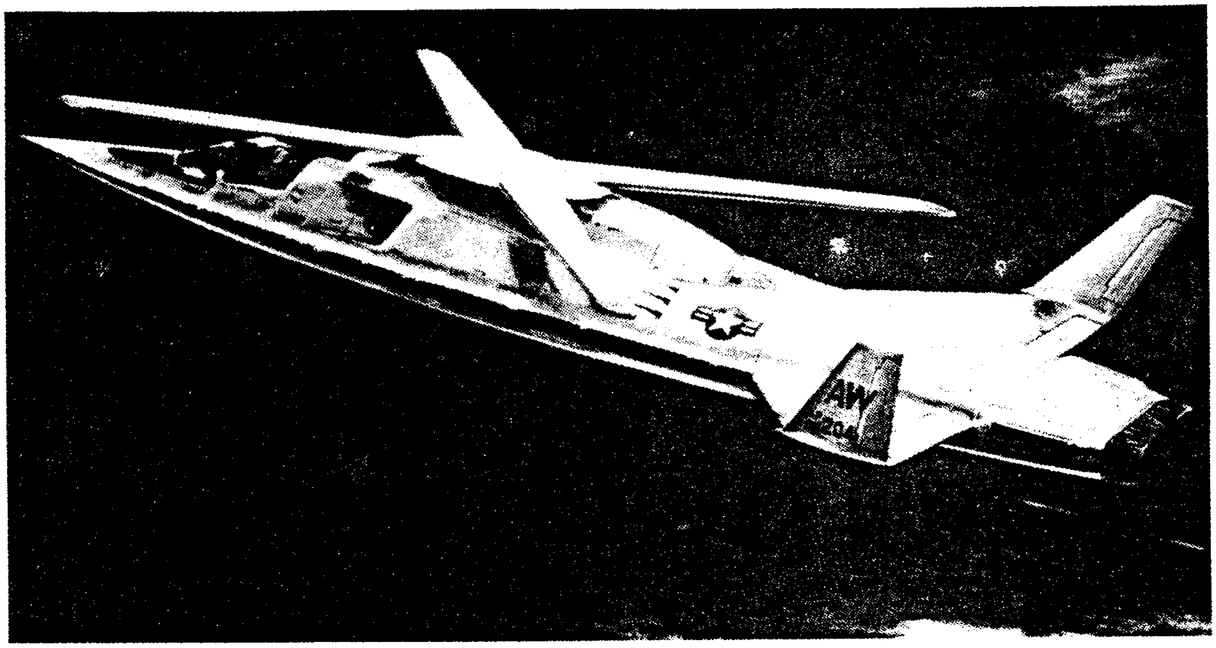

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Figure A-3. Advanced X-wing aircraft concept.

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Figure A-4. The tiltfold concept.

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Candidates for the 350- to 500-Knot Cruise Speed Range

In the speed range of interest for this investigation, the pure and compound helicopters are not likely to see productive cruise speeds reaching up to the bottom of the range. At the other end of the spectrum, the high disk loading lift-jet concept, which is currently represented by the Harrier, is not really intended to be able to use hovering for any extended period in proximity to ground personnel. Power requirements are such that one-engine inoperative hover capability for the lift-jet and the lift-fan types are not likely to be feasible while preserving efficient subsonic cruise power levels.

The propeller types- The aircraft using propellers for cruise will see improvements in their efficiencies within the speed range of interest to this study, 350 to 500 knots, and so, should be considered further. These include the tiltrotor, a variant of this type, the variable diameter tiltrotor, and the tiltwing. The tiltwing category can cover a broad range of disk loadings from those having large rotor sizes like the tiltrotor to the small, high-powered propfan. Generally, the propeller types will encounter a drop-off in propulsive efficiency as design cruise speed is increased to the high subsonic. The propfan has succeeded in increasing the cruise efficiencies to the high subsonic range through swept leading edges, full-span thin sections, appropriate blade twist, and careful hub spinner design. However, the propfan hover efficiency is generally handicapped by its high disk loading, and therefore is not a candidate as the lift system to be used in OEI hover missions.

The stopped rotor types- The various stopped rotor concepts that have been proposed have all employed cruise-fan propulsion means suitable for high subsonic speeds. These concepts have employed rotor in-flight stopping in one of two ways: either with the rotor shaft perpendicular to the flight path or aligned axially with the flight path.

Rotor shaft perpendicular to flight path: Bell and other companies have stopped and started rotors in the wind tunnel to advance ratios far in excess of 1.0 while acquiring blade load data. The latest in the evolution of this approach is the X-wing concept. In the X-wing, the edges of the rotor blades are pneumatically formed by leading edge and trailing edge blowing. This approach accommodates the need for each blade to exchange leading and trailing edges as it rotates at high advance ratios beyond 1 while being stopped or started at high cruise speed. The transition of vehicle lift from the rotating rotor in hover to the same rotor stopped as a fixed wing leads to the need for complex mechanical and pneumatic controls and drive system. The use as a manned vehicle with efficient hover requires shaft rotor power and its attendant need for an antitorque system.

Rotor shaft aligned axially with the flight path:

a. Tilt (Forward) Fold. Stopping or starting the rotor in axial flow is like the proven operation with props that feather. The extension of tiltrotor collective pitch range and the provision of blade fold hinges opens up this extension of current tiltrotor technology. Other accessory components include a variable stiffness hub restraint and folded blade restraints. All of such components have been tested in small and large scale lab, whirl and/or wind tunnel tests. This concept, called the tiltfold rotor, has been studied independently previously by Bell, Boeing, and Sikorsky (see refs. A-3 and A-4).

b. Trailing Rotor. Prior to the tests described above, BHTI also conducted tests of the trailing rotor concept which evolved from studies of spacecraft recovery rotors. In this concept the aircraft hovers then flies in autogyro mode with fan propulsion until it is ready to shift vertical lift to the wings. The rotors are tilted aft then folded in axial flight in the trailing position behind the wingtip rotor pods. This tiltfold process also has been demonstrated in small-scale wind tunnel tests. Differences between the tilt-forward and the tilt-aft concepts are relatively small in the hover and high-speed cruise performance areas. Bell's preference for the tilt-forward concept relates to advantages in STOL performance, and attributes concerning flight dynamics and structural dynamics.

Types Selected for Task 1 Analyses

Based on many considerations only partly summarized above, Bell has selected four vehicle types for further tradeoff study in Task 1. These types are selected to provide a solid basis for recommending the technology tasks NASA can undertake to work towards productive rotorcraft with high-speed capability. These four types are:

1. The Tiltrotor (TR)
2. The Variable Diameter Tiltrotor (VDTR)
3. The Tiltwing (TW)
4. The Tiltfold rotor (TF)

Each of the four types are aimed at performing the NASA-defined civil transport missions at 15 and 30 passengers with a stage length of 600 n.mi.

APPROACH FOR CONCEPT EVALUATION

Quantitative

The quantitative evaluation consists of determining the value PR1 for each concept. This requires the following steps:

1. The NASA-defined mission profile, a design cruise speed, and a passenger size is selected as the basis for sizing a point design.

2. Technology constants are established representing "current" technology – that is, representative of starting predesign "this year" with PFRT engines in four years.

3. Design parameters are selected for setting the ratings and geometry of the point design consistent with accepted criteria for hover, maneuver, structure, etc. These design parameters are:

   - Wing loading
   - Wing thickness ratio
   - Disk loading
   - Hover tip speed
   - Cruise to hover tip speed ratio
   - Cruise diameter ratio (VDTR only)
   - Cruise altitude

4. A computer model developed under Bell independent research and development (IR&D) is used to synthesize the conceptual point-design aircraft considered in this study. It is called "Generalized Advanced Rotorcraft Program" (GARP) and performs this process: a trial design gross weight is selected, geometry and transmission and engine ratings are established to meet takeoff and cruise criteria, the mission profile fuel requirements are computed to attain the design range, weight empty is determined, and a takeoff gross weight is calculated. The error between the trial and calculated weight is the basis for a new trial gross weight. When the error is reduced to an acceptable level, the aircraft size solution is achieved (see fig. A-5).

5. The parameters defining PR1, namely, P, D, T, WE, and F now have values and a quantitative score can be calculated. (Note that P and D are fixed for one passenger class.)

6. The process can be started for combinations of the following parameters:

   - Four concepts
   - Two payload categories
   - Five design cruise speeds
   - Three cruise altitudes
   - Three wing loadings
   - Three wing thickness ratios
   - Three disk loadings
   - Three hover tip speeds
   - Three cruise/hover tip speed ratios
   - Three diameter ratios
   - Two technology levels

Not every combination is completed. Some combinations cause gross weights beyond the range of interest and exceed the bounds of applicability of portions of the synthesis model. Not all combinations are automatically started. Examples include: diameter ratios apply only to the VDTR concept; advanced technology is applied only to the 450-knot design cruise speed; and others. The point designs are synthesized as described above and the output data

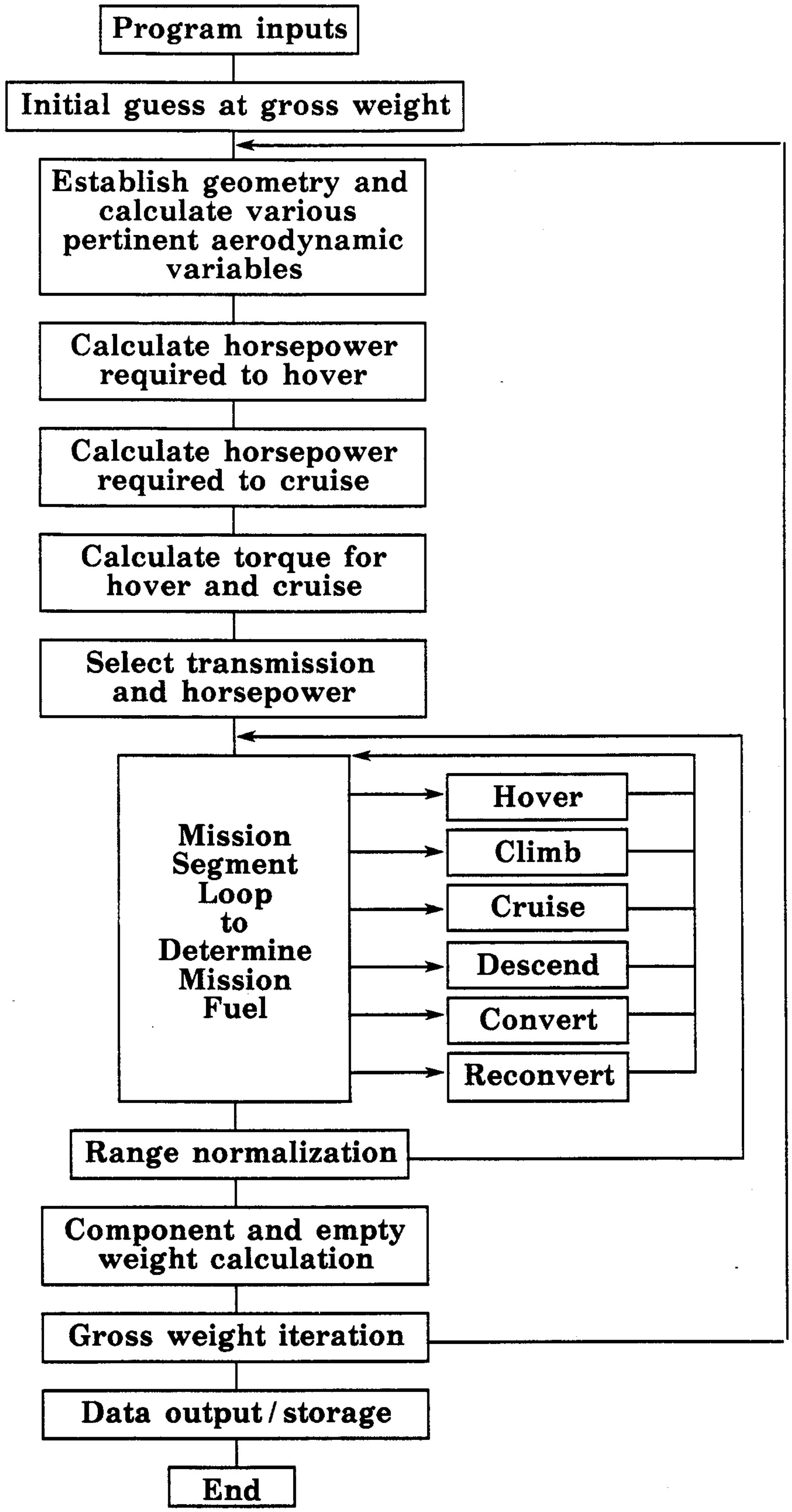

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Figure A-5. Task 1 synthesis flowchart.

are organized in references A-1 and A-2. Reference A-1 (Book 2) has the tabulated data for the 30-passenger aircraft and reference A-2 (Book 3) has the 15-passenger data.

Qualitative

The qualitative discussions are aimed at those attributes that influence the parameters in the general productivity expression, PR, not covered by the quantitative data.

QUANTITATIVE RESULTS

Performance of Each Concept with Technology Fixed

Comparison overview- The data for the 30-passenger aircraft is used to illustrate many of the trends for each concept. Current technology is assumed and shows the speed range in which each concept is most productive. Data for the 15-passenger aircraft follow similar trends except at a lower level of productivity due to scale effects.

The productivity index, PR1, defined in the paragraph entitled "Selected Missions and the Related Productivity Index," is shown versus design cruise airspeed in figure A-6. The total population of the 30-passenger Task 1 point designs of each of the four aircraft types is presented in subfigures (a) through (d). These graphs contain many design parameter combinations that are clearly non-optimum. Since the airspeed values investigated are at 25-knot intervals from 350 to 500 knots, point designs cluster only along these speed values. The envelopes of the top of the population of data points represent the "cream of the crop" and illustrate the best of many possible combinations of design parameters. The envelope of the bottom of the scatter represents inefficient combinations of design parameters that lead to high gross weights. In many cases, the Task 1upper bound of 100,000 lb gross weight is evident at higher speeds as a clipped data band.

The following can be observed:

1. The tiltrotor has the highest productivity of the four types studied in the speed range of 350 to 500 knots.

2. The speed for highest productivity is 375 knots.

3. The tiltwing is a close second up to about 400 knots where it edges out the tiltrotor.

4. The VDTR does not show up as good as either the tiltrotor or the tiltwing.

5. None of the propeller types perform the mission at 450 knots at less than 100,000 lb gross weight.

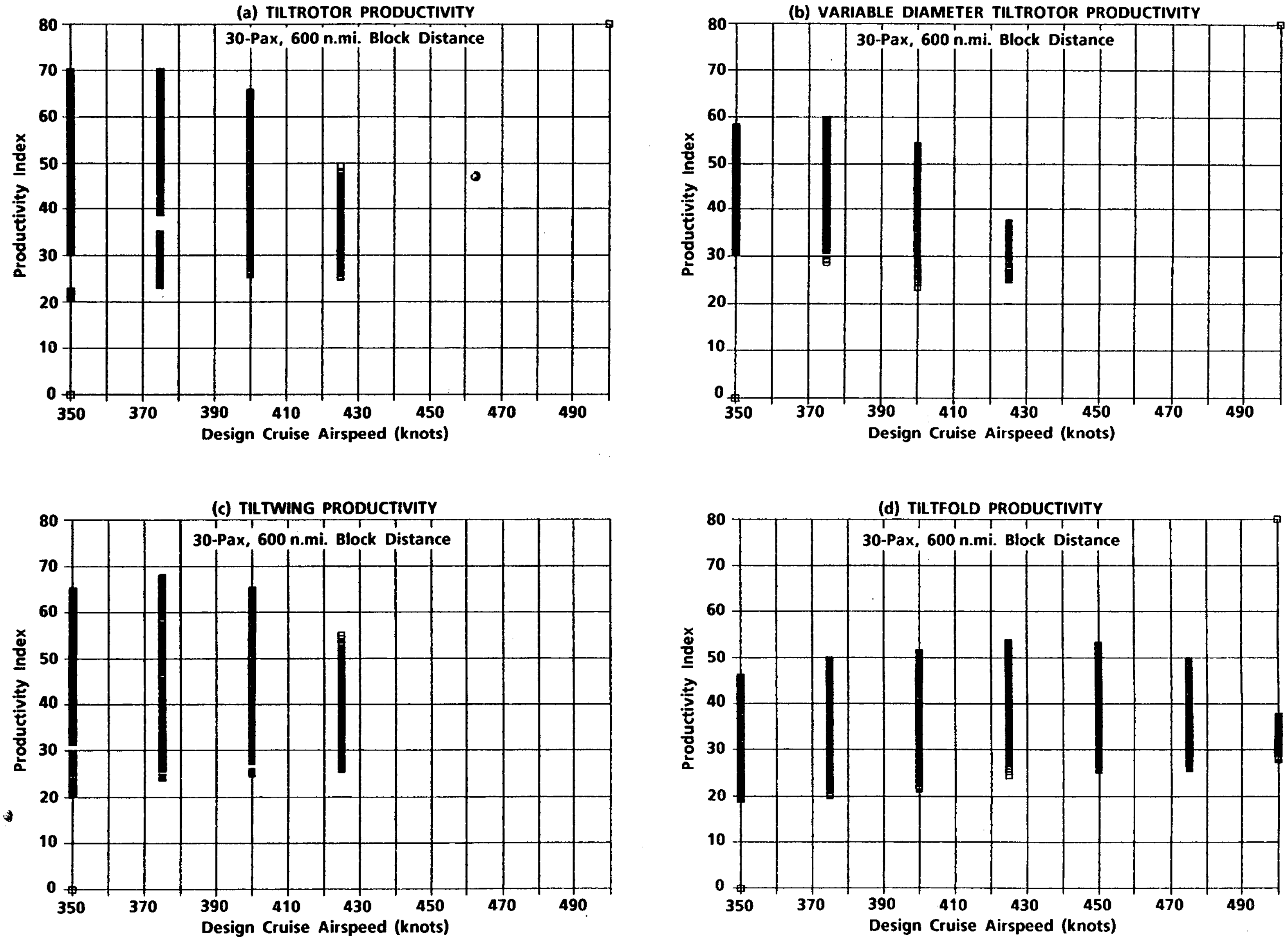

Figure A-6. Productivity vs. cruise speed (350 to 500 knots).

6. The tiltfold has better productivity than all other types investigated at around 430 knots and above.

Design parameter tradeoffs for maximum productivity- An example is presented of tradeoffs of vehicle design parameters from the population of 30-passenger tiltrotor point designs. The database for the tiltrotor can be found in reference A-1. This process also shows the sensitivity (or lack of it) to the design parameters varied. The process is an approximate one for choosing the design parameters leading to a high productivity design point for Task 1.

a. From figure A-6 (a), only those point designs at the maximum productivity speed of 375 knots are selected for further sifting; others are discarded.

b. From figure A-7, the above points are plotted versus the design hover tip speeds investigated. At 820 fps, compressibility is seen to take effect. The tip speeds of 780 and 800 are nearly equal in productivity with a slight advantage at 800 fps. These points are selected for further review. (Task 2 included the assessment of sideline noise levels in selecting tip speeds.)

c. The next tradeoff is of the ratio of cruise to hover tip speed. The range selected is based on experience of past studies wherein the ratios shown in figure A-8 were possible optimums. This study shows that the ratio of .77 yields the best compromise of component weights, power and fuel economy for this mission. The point design at the other ratios are discarded and those at .77 are carried forward to the next review.

d. The next design parameter to be selected is wing loading and the option range is shown in figure A-9. Lower wing loadings have advantages of lower conversion corridor speeds and increased volume in the wing for fuel. Higher wing loadings reduce the wing surface exposed to rotor downwash in hover and therefore hover download. High cruise speeds also optimize out with higher wing loadings. However, a wing loading of 120 psf was selected as the maximum allowable to preserve maneuver margins at conversion speeds under 200 knots. From performance considerations illustrated in figure A-9, the maximum allowed wing loading is selected. The residual points at 120 psf are carried to the next review.

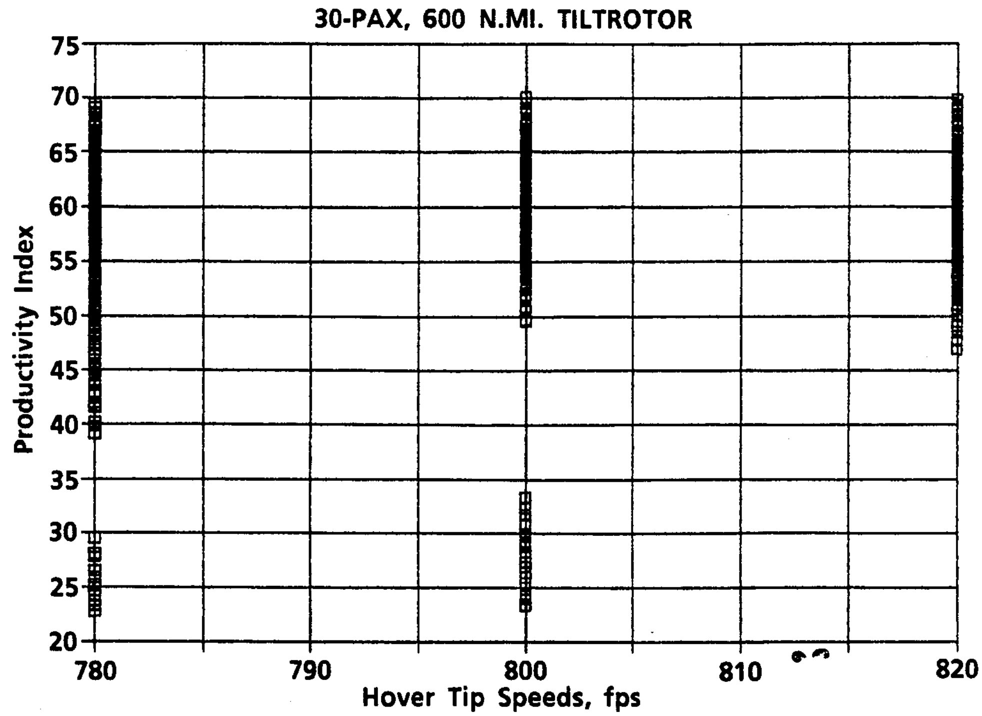

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Figure A-7. Productivity vs. hover tip speed.

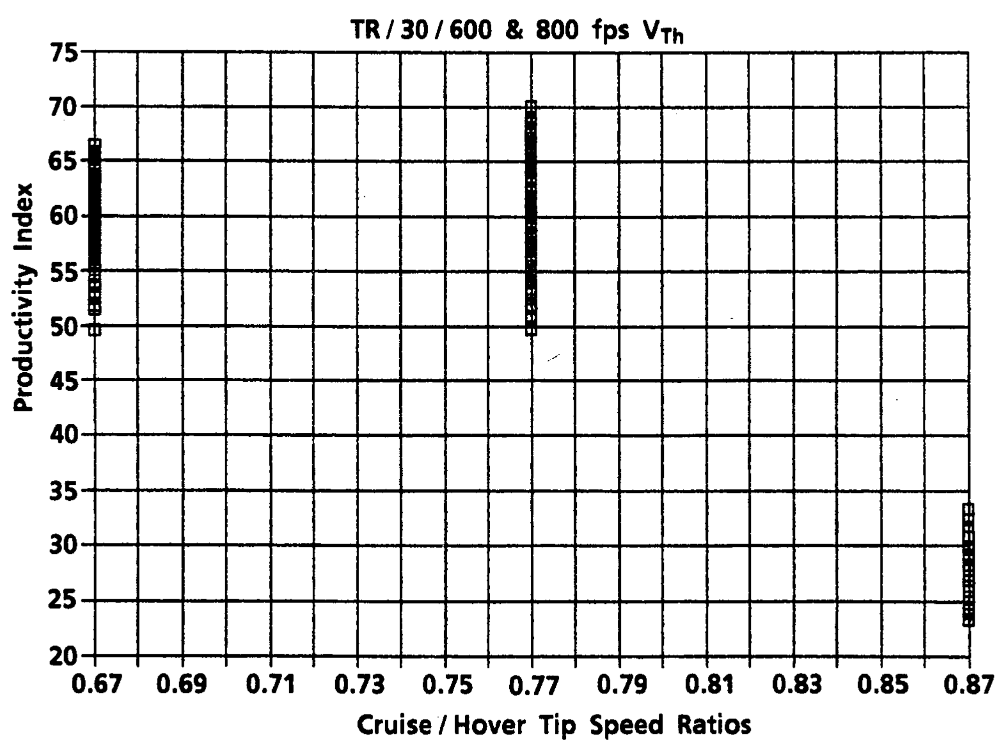

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Figure A-8. Productivity vs. cruise-to-hover tip speed ratio.

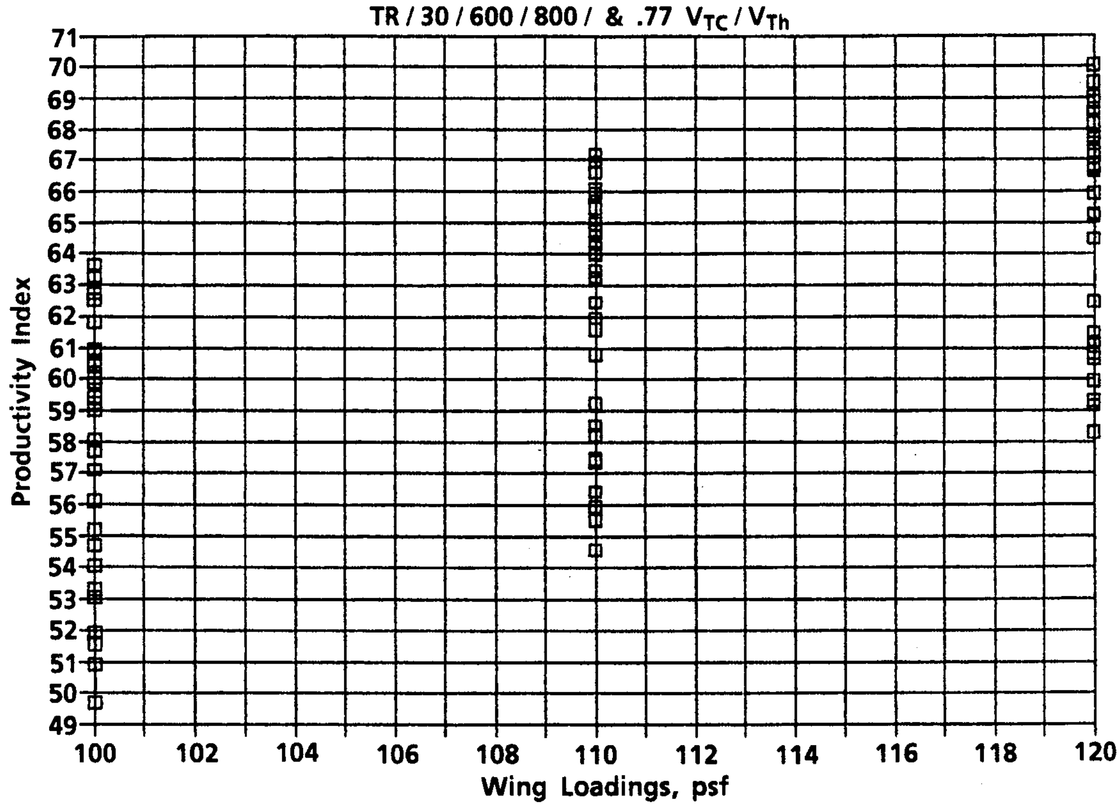

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Figure A-9. Productivity vs. wing loading.

e. The point designs having 120 psf wing loading are reviewed for best disk loadings (fig. A-10). Lower disk loadings provide better hover efficiency but require a larger wing span. For short duration cruise missions, this might not pay off but in this case the lower disk loading point designs are more productive. The lowest disk loading investigated, 18 psf, is selected.

f. The question of best cruise altitude depends on the definition of "best." It may be selected to minimize time (fly low), minimize fuel (fly high), or minimize direct operating cost (fly in between). Note that the productivity index is helped by flying low in that it contains time, T, as a parameter; it is helped by flying high in that fuel load, F, is a parameter; and its supposed to reflect direct operating cost. Another effect is evident in weight empty, WE, influenced by engine weight and aircraft size. As design cruise altitude is increased, a more powerful engine is needed to provide sufficient power at altitude when allowing for the altitude lapse rate of engine power. These effects combine when using PR1 as the basis of tradeoff, to select, for this vehicle concept, the lowest cruise altitude allowed, 15000 ft (see fig. A-11).

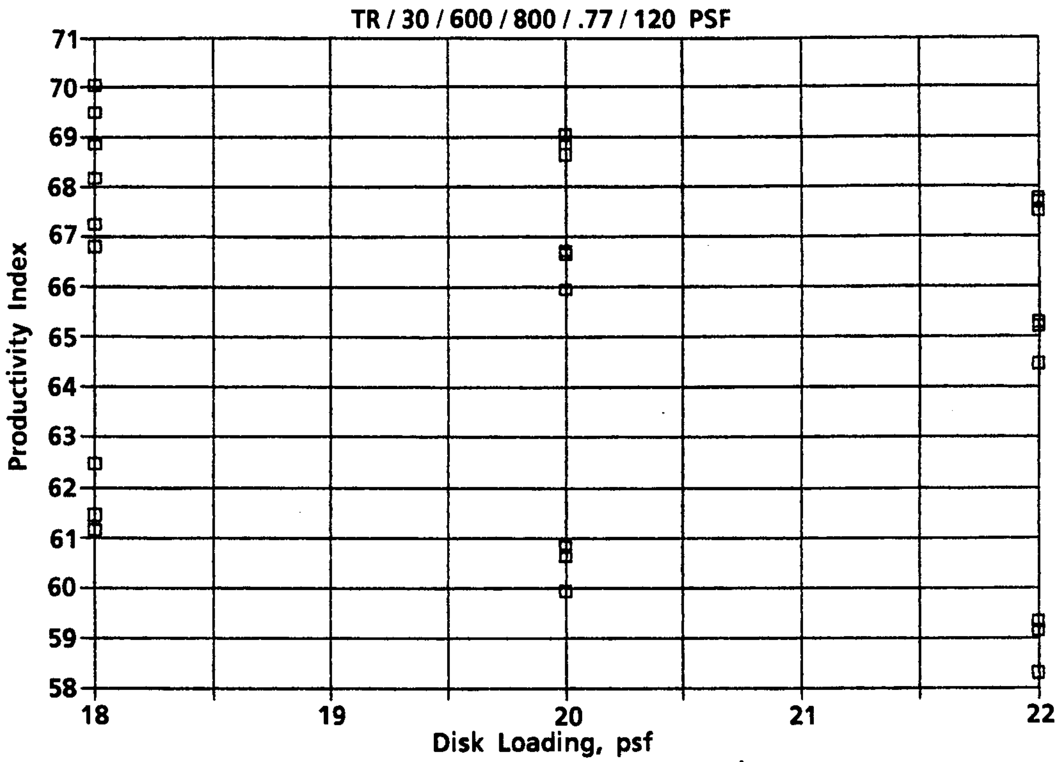

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Figure A-10. Productivity vs. disk loading.

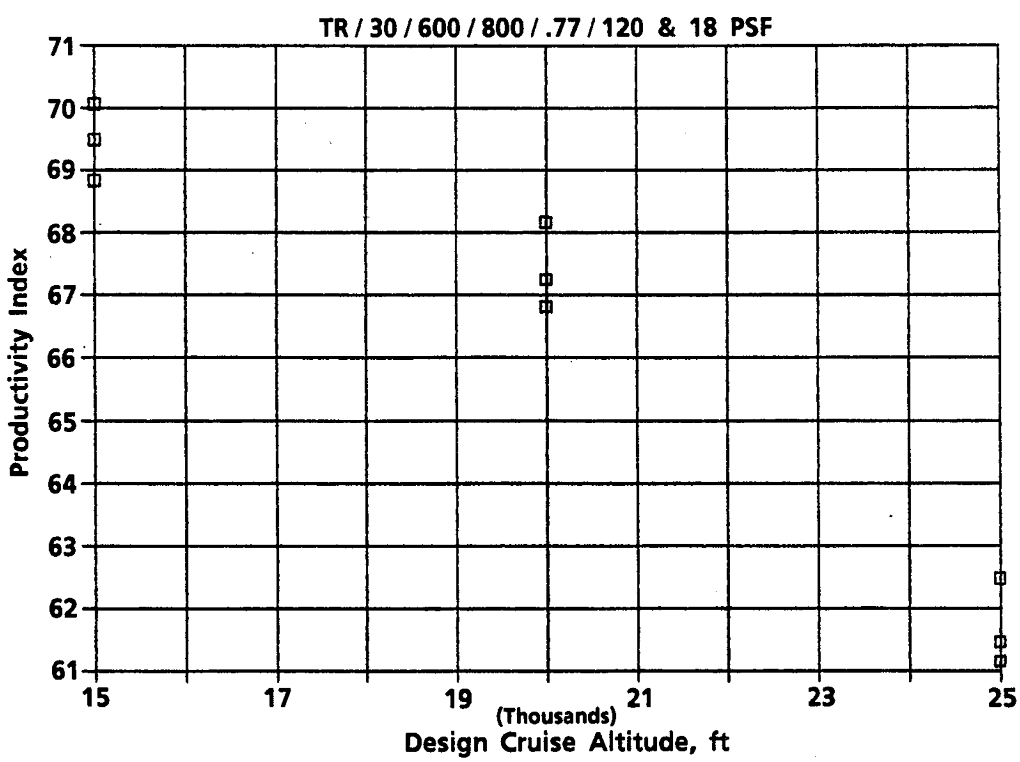

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Figure A-11. Productivity vs. cruise altitude.

g. At this step in the tradeoff process, only three point designs remain. The best wing thickness ratio for this mission profile is 21% thick. A higher resolution sweep of wing thickness in this case would show little difference in PR1 and gross weight for variations of $\pm 1\%$ (see fig. A-12).

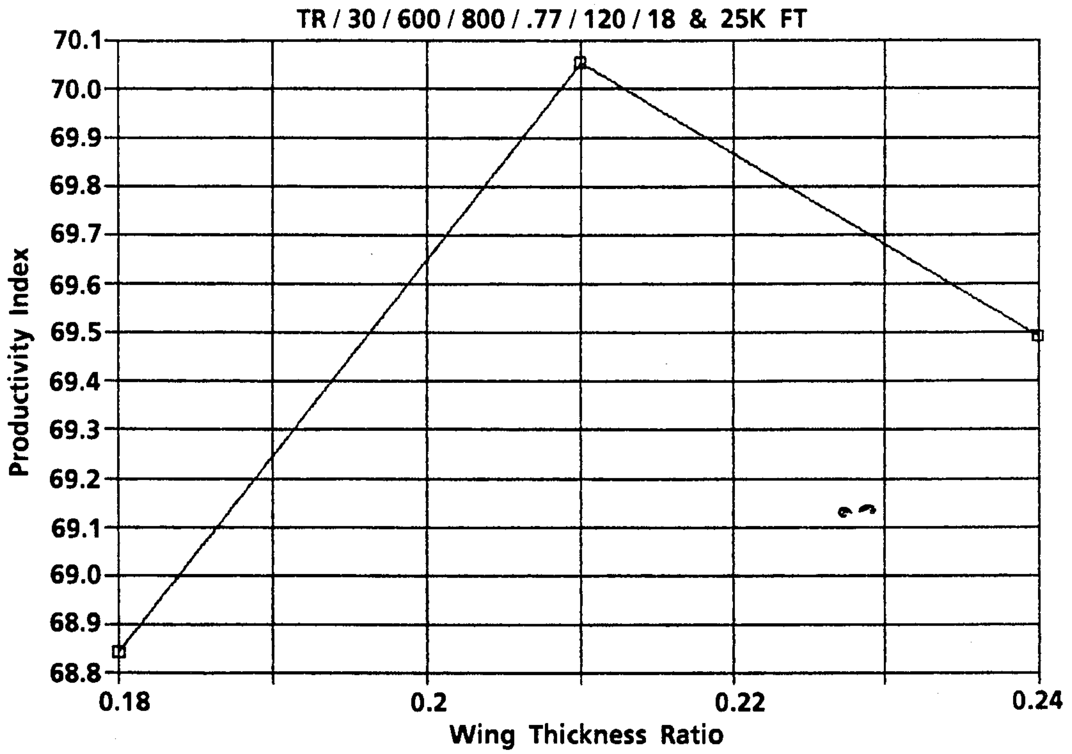

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Figure A-12. Productivity vs. wing thickness ratio.

It should be noted that if the design around rules required that ALL fuel be carried in wing cells only, there would be a constraint on the selection of the above design parameters. The selection would tend toward thicker wings and/or lower wing loadings which would lower the productivity and increase the design gross weight of the solution designs. Further, there would be a unique handicap placed on the tiltwing concept which has not employed wing fuel cells in the past. The ratio of mission fuel required to wing capacity outboard of the fuselage is tabulated in references A-1 and A-2 for reference but is not used to constrain the selection of design parameters in Task 1.

The point design having the best productivity index in figure A-12 is shown at a value slightly over 70. This point can be found on data page 15 of Section 1.1.3 in reference A-1. An excerpt of the tabulated data is presented in table A-1 and shows that the point has a design gross weight (GW) of 37,001 lb. The extended data in reference A-1 shows a productivity index of 70.1. Additional details concerning engine ratings, rotor diameter, geometry, weights and drag breakdowns can be found for that point in the corresponding sections of reference A-1.

Table A-1. EXCERPT OF TABULATED DATA IN REF. A-1, TILTROTOR, 30-PAX

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	A	B	C	D	E	F	G	H	I	J	K
990		375	800	0.77	110	22	1	25000	0.24	44794	11931
991		375	800	0.77	120	18	1	15000	0.18	37512	7128
992	>>>>>	375	800	0.77	120	18	1	15000	0.21	37007	7169
993		375	800	0.77	120	18	1	15000	0.24	37294	7461
994		375	800	0.77	120	18	1	20000	0.18	37983	7909
995		375	800	0.77	120	18	1	20000	0.21	37396	7925
996		375	800	0.77	120	18	1	20000	0.24	37891	8309
997		375	800	0.77	120	18	1	25000	0.18	40535	9778
998		375	800	0.77	120	18	1	25000	0.21	39857	9774
999		375	800	0.77	120	18	1	25000	0.24	40499	10286
1000		375	800	0.77	120	20	1	15000	0.18	37518	7211
1001		375	800	0.77	120	20	1	15000	0.21	37476	7365
1002		375	800	0.77	120	20	1	15000	0.24	37692	7612
1003		375	800	0.77	120	20	1	20000	0.18	38081	8039
1004		375	800	0.77	120	20	1	20000	0.21	38108	8195
1005		375	800	0.77	120	20	1	20000	0.24	38535	8543
1006		375	800	0.77	120	20	1	25000	0.18	40829	10013
1007		375	800	0.77	120	20	1	25000	0.21	40789	10181
1008		375	800	0.77	120	20	1	25000	0.24	41381	10663
1009		375	800	0.77	120	22	1	15000	0.18	38094	7541

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Using a similar selection process for each aircraft concept, the geometric design parameters of wing span, chord, diameter, etc., were identified at the design cruise speed for maximum productivity; generally 375 knots for the three propeller types and 450 knots for the tiltfold. (See ref. A-1 for detailed geometric parameters of all 30-passenger point designs.) Three-view sketches were made of the tiltrotor, tiltwing, and tiltfold. These are presented in figures A-13, A-14, and A-15, respectively. The VTDR would appear similar to the tiltrotor in cruise mode except that the wing would be slightly larger and rotor diameter would be about 85% of that shown. As design speed specifications are increased, lift-propulsion geometry would get stockier quickly reflecting the rapid rise in design gross weight. The layouts shown are for three-abreast seating. To provide more volume for baggage, a four-abreast seating configuration was synthesized for the 30-passenger size. Both seating arrangements for 30 passengers are tabulated for the 450-knot, advanced technology point designs in reference A-1.

Productivity - gross weight correlation- The question of validity of the productivity index is generally resolved by comparing the conclusions drawn by using it to those drawn by observing trends of gross weight. That process will lead to very nearly the same conclusion when comparing different aircraft types; i.e., given that all other mission capabilities are equivalent, then the lower weight is the more desirable. However, using design gross weight as a selection criterion generally will favor the slower cruise speed, if

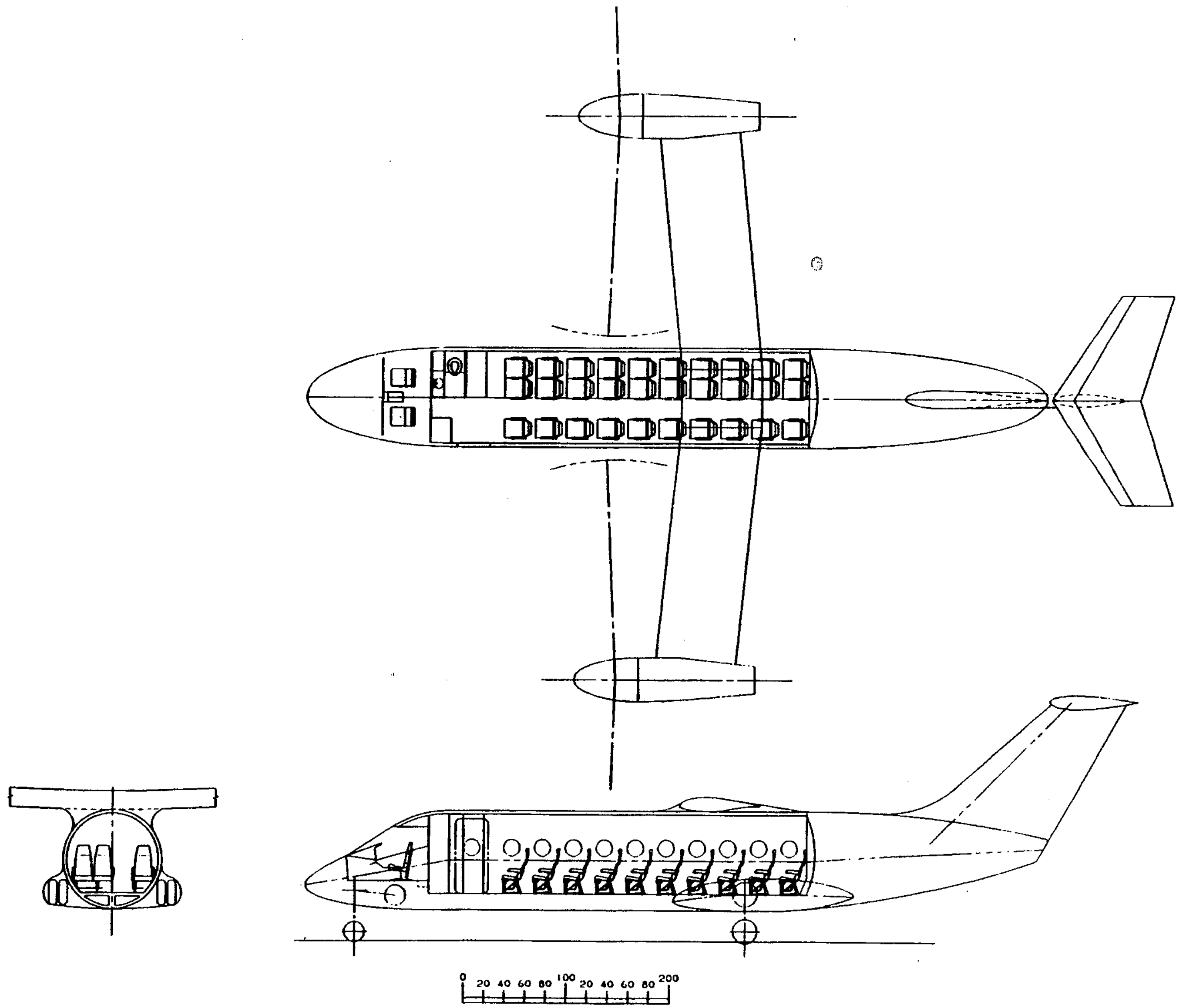

Figure A-13. 3-View sketch, tiltrotor

R240

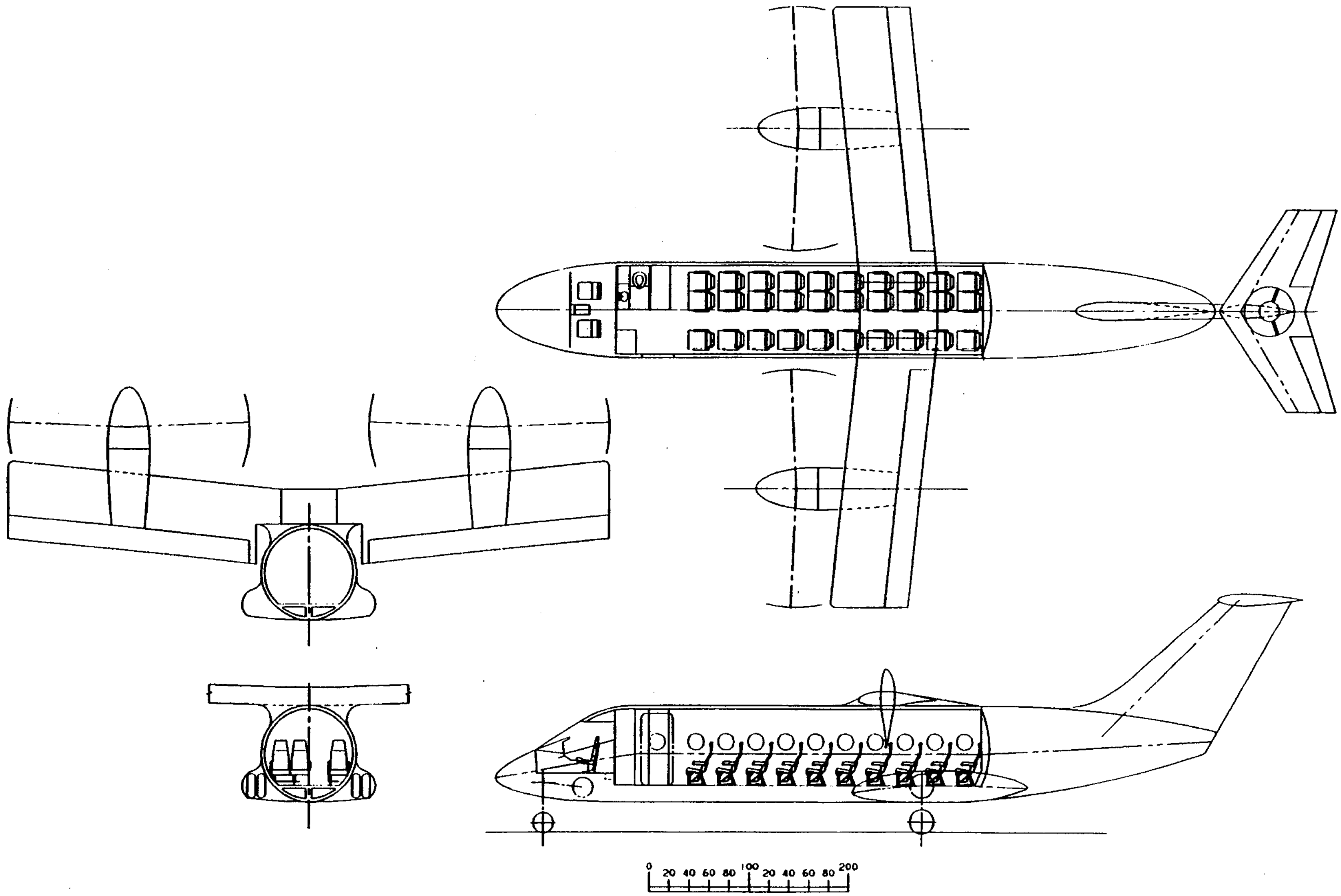

Figure A-14. 3-View sketch, tiltwing

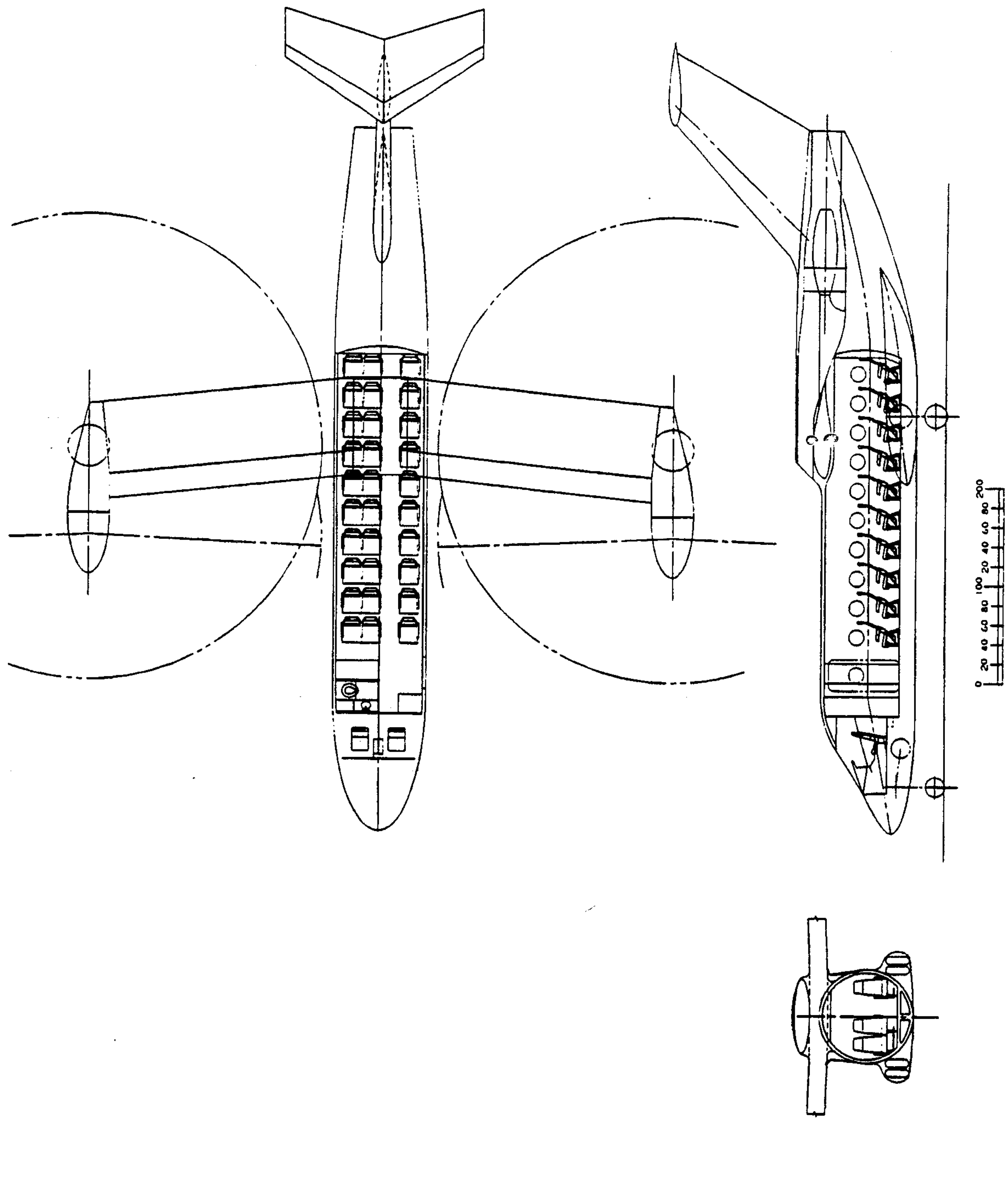

Figure A-15. 3-View sketch, tiltfold

R242

speed is in contention among the alternatives. What is then needed is the productivity type of measure to credit the candidates with the ability to conduct more sorties per day or to produce more passenger trips per day.

The design gross weight for each point design may be observed as a function of speed. Figures A-16 (a) through (d) present such data for the four types, and for all cases, synthesized in the 30-passenger category. The best designs at any speed will be among the lightest, and the heavier designs will represent non-optimum solutions. By looking at the trend of gross weights as speed is varied, the impact of the speed specification becomes evident. The propeller concepts exceed 100,000 lb GW as 450 knots is approached. When the solution gross weights exceed 100,000 lb, the math modeling of weight estimation algorithms depends significantly on extrapolation beyond current trend data. In some cases, this results in erratic convergence behavior and indicates the "risk" of parametrically defining such designs. (It does not mean they cannot exist, just that more detailed design studies are required to provide some form of data base if a more economical alternative does not appear.)

What seems to be evident *from a weight standpoint* is that:

1. Slower is "better" (not the whole story)
2. The propeller types get to be very weight sensitive to the speed specification
3. There are a lot of ways of designing non-optimum designs
4. Intuitively, "good" designs must occur at the speeds before the weight break occurs.

Practical designs will be close to, but not necessarily at, minimum weight for any given design speed. The productivity index is a better criterion for selecting the blend of minimum gross weight and design cruise speed because it considers how quickly revenue or military effects can be generated. The interplay of gross weight and productivity becomes more evident as different size classes of aircraft are compared. This is shown in the next section.

Size effects- At what passenger load factor can we expect improved productivity by switching to a smaller size aircraft given a fixed demand? It is expected that economies of scale will show that the well-designed larger aircraft can be more productive than the well-designed smaller one. The question is addressed in this section by comparing the 30-passenger and 15-passenger point designs. The approach is to compare both the productivity index (vertical scale) and the design gross weight (horizontal scale) for all point designs in both passenger classes. Because there is a correlation between both measures, the expected form of this plot is that the best designs (lowest weight and highest productivity index) will congregate at the upper left of the trend data and the poorer ones will trail off to the lower right in "comet" fashion. Only those points at the head of the comet are of interest unless other specifications or constraints on the designs forces consideration

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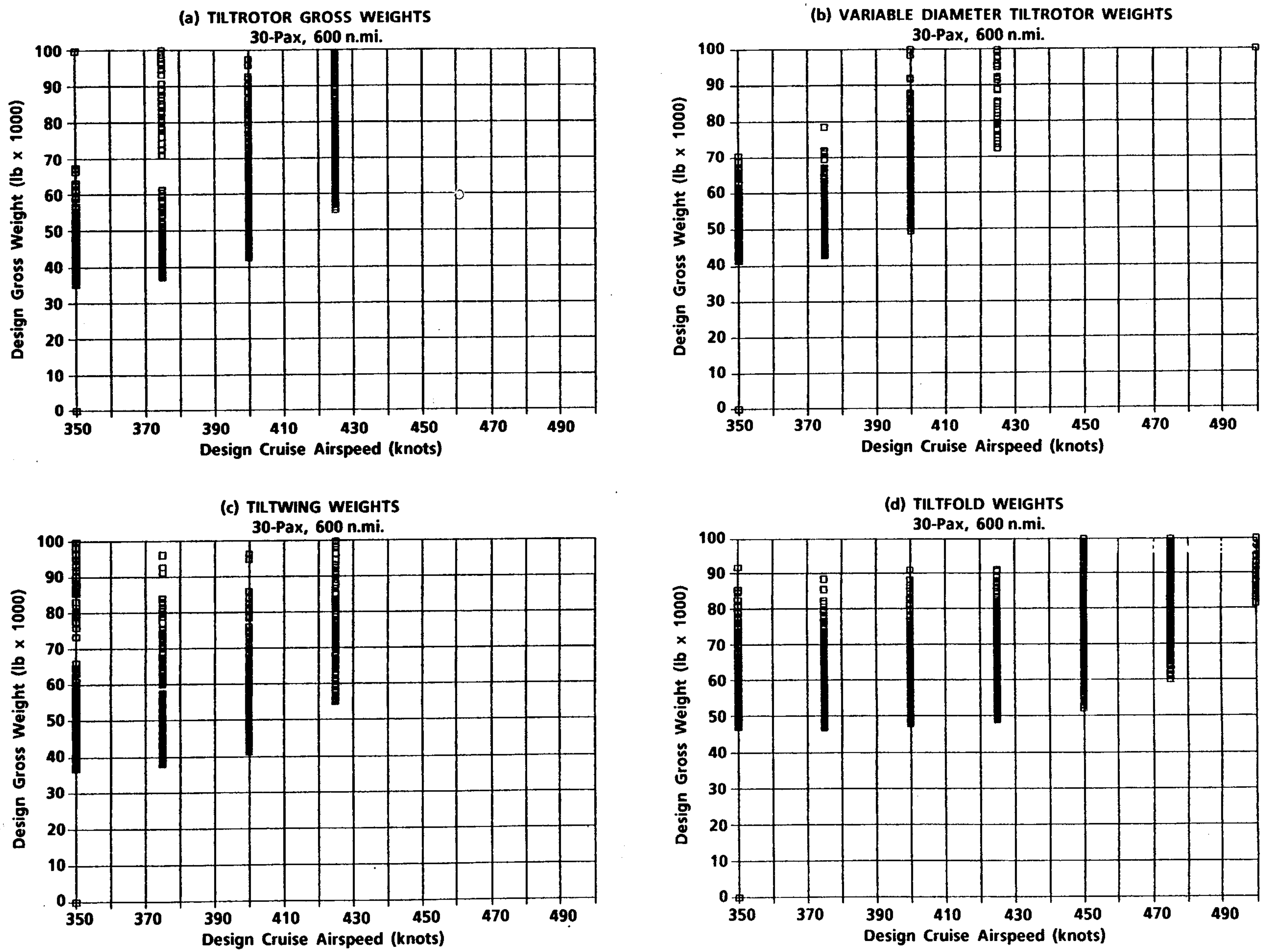

Figure A-16. Gross weights vs. cruise speed.

of less productive solutions. Comparisons are made for vehicles of each type in figures A-17 through A-20. Twin comet curves are formed on one graph for each concept, the lower curve representing the smaller size aircraft. For each size aircraft, bands appear for each cruise speed. (More speed bands exist for the tiltfold making busier comets.) The envelope of the data at the comet head shows the variation of gross weight and productivity versus speed for the best points. This illustrates how productivity and weight selection criteria can yield different solutions for selecting the "best" mission speed specification.

A general view of all the data indicates that the 15-passenger aircraft has approximately 65% of the productivity of the 30-passenger aircraft when both operate with the same passenger load factor. If demand is fixed and the 30-passenger aircraft load factor falls below about 65% then the 15-passenger aircraft (given the same level of acceptance) would have the higher productivity because it flies closer to capacity. This is a situation where Scenario #3 of the section on tailoring (pg. A-5) applies. In this example, both aircraft would have essentially the same values of the productivity index as defined there.

Another observation is that as cruise speeds for the propeller types go beyond 425 knots, the productivity index values, while finite, are becoming insignificant because the solution gross weights are not parametrically reliable. The tiltfold option presents a more stable solution and a higher productivity alternative at lower weights for speeds over 425 knots.

The tiltrotor data shows that the 30-passenger aircraft peaks in productivity at 375 knots whereas the 15-passenger aircraft peaks at about 350 knots. This is another ramification of size. The larger aircraft tends toward higher speeds because its drag does not grow as fast as its weight and because the higher powered engines are more efficient. Larger size is better if the demand is there.

Effects of Technology Variations

The technology-productivity matrix- Identifying technology that helps the user achieve his objectives is the goal of the High Speed Rotorcraft Technology program. The productivity index provides a yardstick for doing this. It requires, however, that the technology areas of interest to NASA be further defined by their relevant technical elements and that these be related to the terms directly used in the productivity index selected. Table A-2 addresses these relationships and shows how they involve both quantitative and qualitative links.

The first column lists the technology areas of interest to NASA. The second column identifies several key elements in each area that, in turn, may be represented in detail by other technical parameters. The third column lists the term in the productivity index expression affected by that technical element. Some of the elements influence more than one index term. The fourth column reflects the sensitivity of the math synthesis model used in this study for investigating numerical changes in the related parameters. (Many other technology parameters can be addressed but the ones shown are believed to include the major players.)

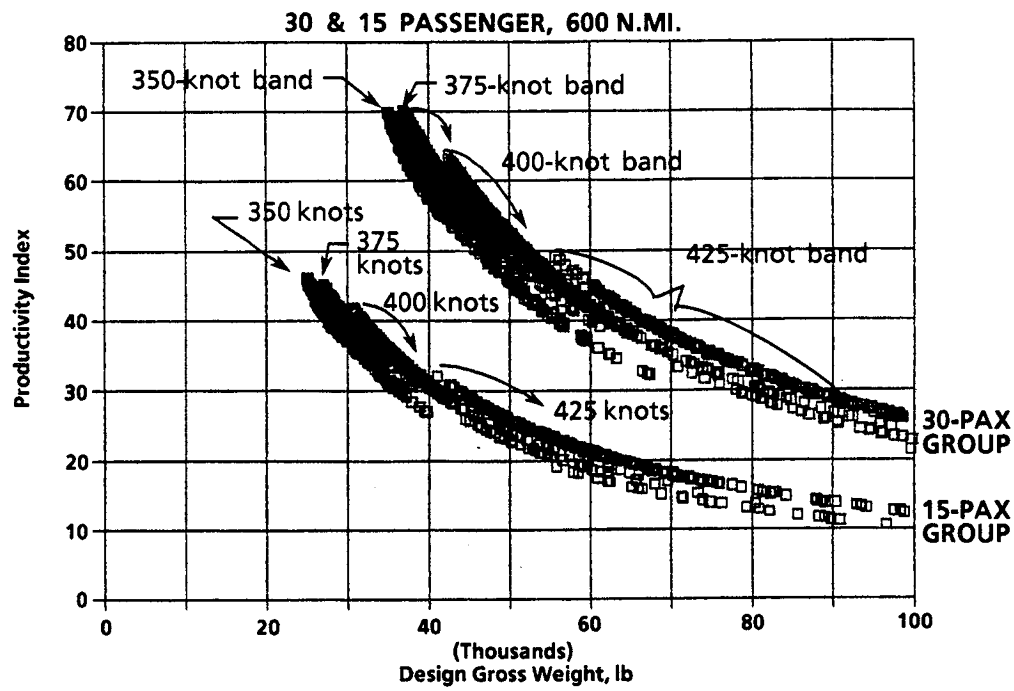

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Figure A-17. Size effects - tiltrotor.

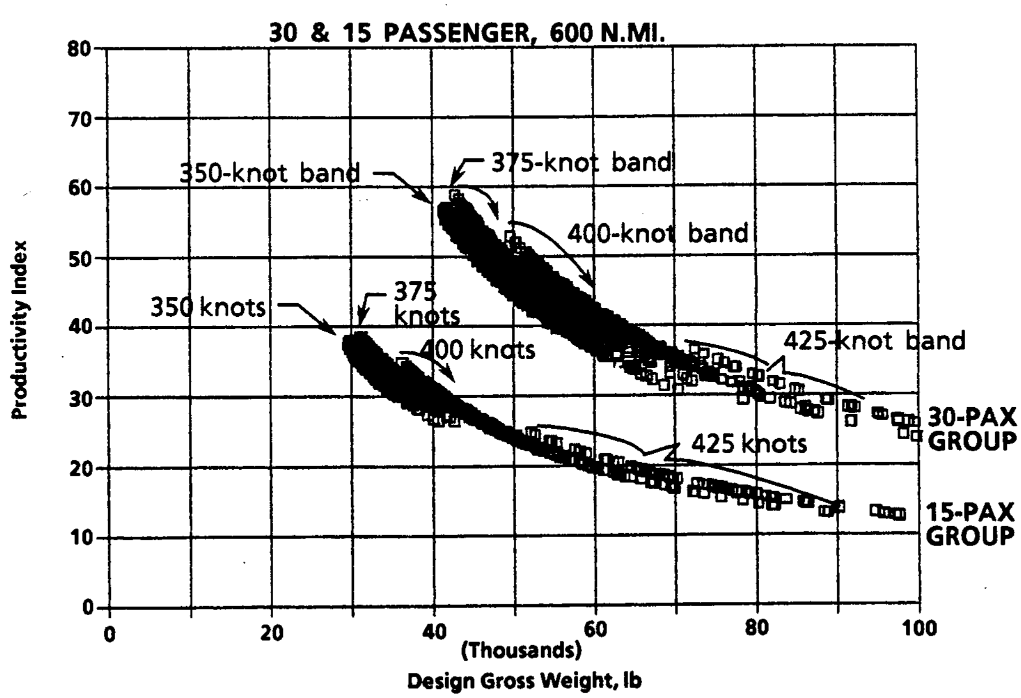

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Figure A-18. Size effects - VDTR.

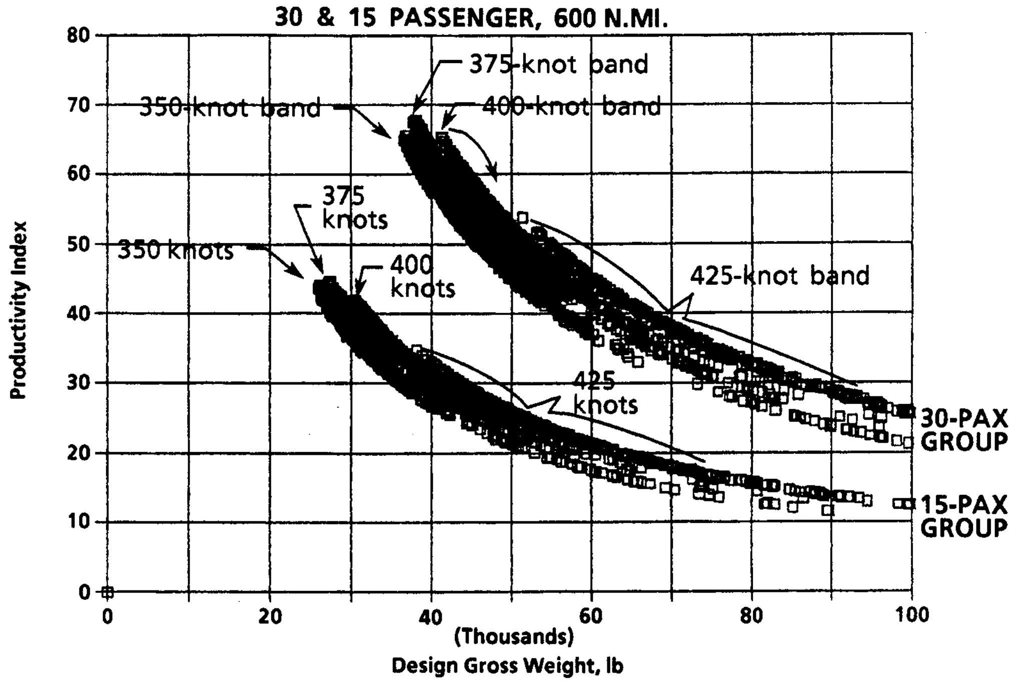


Figure A-19. Size effects - tiltwing.

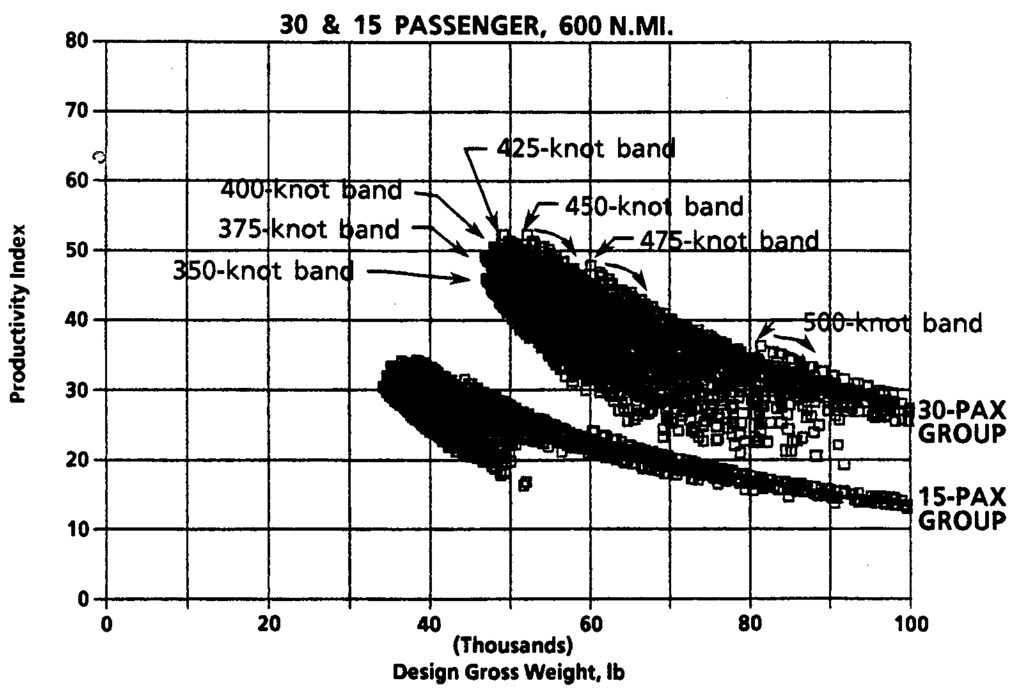


Figure A-20. Size effects - tiltfold.

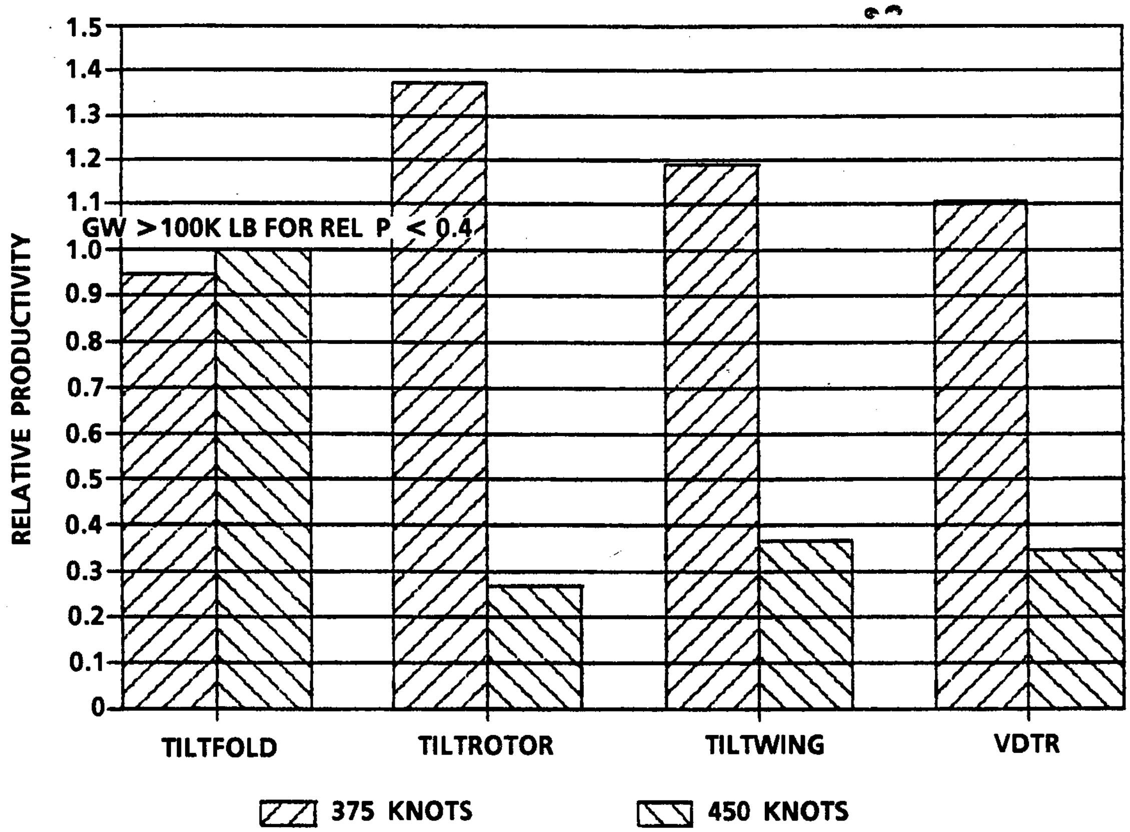
Table A-2. TECHNOLOGY AREAS ADDRESSED

Technology Area	Technical Element (Parameter)	General Productivity Index Parameter	Quantified (Prod.Index)	Qualitative Only
Propulsion	No. of Engines	Availability	-	X
	No. of Engines	Survivability	-	X
	Specific Weight	Weight Empty	X	-
	SFC	Mission Fuel	X	-
	Pwr Temp/Alt lapse	Weight Empty	X	-
	Pwr Temp/Alt lapse	Mission Time	X	-
	Drive system speeds	Weight Empty	X	-
Materials	E, G, f, density.....	Weight Empty	X	-
	Observable Attributes	Survivability	-	X
Aerodynamics	Wing $C_{L_{max}}$	Weight Empty	X	-
	Wing $C_{D_{Mdd}}$	Weight Empty	X	-
	Wing $C_{D_{Mdd}}$	Mission Fuel	X	-
	Prop (C_L/α) M_{dd}	Weight Empty	-	X
	Prop $C_{D_{Mdd}}$	Mission Fuel	X	-
	Concept comp. drag	Mission Fuel	X	-
Flight Dynamics	Wing $C_{L_{max}}$	Weight Empty	X	-
	Rotor C_T/σ_{max}	Weight Empty	X	-
	Tail Vol Coefficient	Weight Empty	X	-
	Tail Vol Coefficient	Mission Fuel	X	-
Control System	No. of Actuators	Weight Empty	X	-
	No. of Actuators	Survivability	-	X
	No. of Actuators	Availability	-	X
	Control laws	Weight Empty	X	-
Electronics	MTBF, MTTR	Availability	X	-
	Function density	Weight Empty	X	-
Structural Dynamics (Vibration, Aeroelasticity)	MTBF, MTTR	Availability	-	X
	Wing strength, freq	Mission Fuel	X	-
	Wing strength, freq	Weight Empty	X	-
	Ride quality (g's)	Pax Load Factor	-	X
Noise	Rotor tip shapes	Survivability	-	X
	Cabin ambients	Pax Load Factor	-	X
Mechanical Concept	MTBF, MTTR	Availability	-	X
	# of new functions	Weight Empty	X	-
	# of alternate modes	Survivability	-	X
Flight Procedures	Conversion steps	Mission Time	X	-
Mfg. Tech. & Diagnostics	Development time & maintenance rates	(Multipliers)	-	X

Not all influence on the index will be quantifiable and therefore some elements can only be addressed qualitatively early in the conceptual stages. As systems engineering progresses, the relationships indicated by table A-2 will be expanded. The work planned for Task 3 will cover each of the areas listed in more detail.

Technology variations from baseline- The point designs presented in the Quantitative Results section entitled "Performance of Each Concept with Technology Fixed" (pg. A-13) are all representative of what is called "current" technology. This means the technology that could be applied to the predesign of the aircraft starting "this year" with engine PFRT in four years. For example, convertible engines have been run in several versions, and large-scale variable geometry rotors have been tested since the early 70's. It would be expected however that key components would have to undergo validation testing otherwise the aircraft would be simply a rehash of older generation types.

The results of applying current technology thus defined in terms of how each aircraft concept performs at the desired speed of 450 knots is shown in figure A-21. In addition, the comparison is made for the speed at which productivity peaks, 375 knots. The relative productivity is normalized to the tiltfold concept which has the best rating at 450 knots.



R249

Figure A-21. Productivity comparison, 30-pax, current technology.

The fact that the remaining types show any productivity value at all at 450 knots should be tempered by the understanding that all of them have gross weights in excess of 100,000 lb as estimated by the math model used. In effect, the tiltfold concept is the only viable candidate based on these ground rules. Can the other concepts be brought into contention if technology is accelerated for them?

This requires that the baseline technology parameters be visible for the point designs representing current technology, then the incremental variations in the same technology parameters be identified for each concept when applicable. Table A-3 presents the variations studied in Task 1. The baseline values for the technical elements that were varied are shown at the top block of table A-3 for the four aircraft types. In some cases, the elements are referenced to a class of data rather than a single number (e.g., T406 engine curve). This block serves also to show the baseline relationships among the four types such as assumed relative rotor system weights.

The technology excursions were made by grouping changes involving one or more related technical parameters. This makes it easier to visualize the influence of areas of technology parameters. No details are assumed on how to realize these excursions at this point.

The first category is general technology that involves parameters that will affect all four concepts (the "safe" way to allocate resources). The system level parameters here are engine specific weight and specific fuel consumption assumed to be 80% of current technology. Integrated High Performance Turbine Engine Technology (IHPTET) goals address many additional parameters that would roll up into the productivity index, when evaluated, such as reliability, maintainability, and survivability. Another parameter in this first category has to do with wing airfoil improvements that would delay compressibility effects by +.05 Mach number for all types. Another area is drive system technology assumed to produce weights 80% of the current ART (Advanced Rotorcraft Transmission) Phase 1 goals. Pressurized composite fuselage manufacturing methods reduce cost.

The second category applies only to the propeller types. It assumes that, if successful, the propeller maps will behave as though drag divergence Mach effects are delayed by .05. This parameter is varied separately because with assumed baseline technology, propeller efficiencies drop off rapidly above 425 knots and cause the required engine size and fuel loads to cascade the increase in gross weight.

The third category applies to nacelle drag as influenced by the presence of the engines on the wing. This category does not apply to the tiltfold because it has the engines aft in the fuselage and thereby minimizes the size of the wing nacelles. The drag reduction for the other concepts assumed here is 50% by reducing the engine size or otherwise improving high speed flows at the engine nacelles.

The fourth category applies to eliminating a portion of the wing weight due to stiffness needs. The basis for the weight element here is that portion of wing weight over that required to provide jump takeoff strength in the vertical lift mode. It is generally attributed to the need to control wing stiffness to preclude aeroelastic instabilities involving propeller whirl flutter or proprotor flapping. This category of improvement is made available to the tiltrotor, VDTR, and the tiltwing. The stiffness weight increment is not needed in any case

Table A-3. ASSUMED TECHNOLOGY VARIATIONS FOR SENSITIVITY STUDY

	Tiltfold	Tiltrotor	Tiltwing	VDTR
BASELINE REFERENCE FOR "CURRENT" TECHNOLOGY				
Engine SFC at rated shaft power	.48	.40	.40	.40
Engine Wt/shp	2xT406 curve	T406 curve	T406 curve	T406 curve
Prop efficiency map basis	N.A.	V22+	V22+	V22+
Nacelle drag	No engine	With engine	With engine	With engine
Wing weight — Strength Basis Portion	1.0	1.0	.68	1.0
Wing weight — Stiffness Basis Portion	N.A.	Yes	Yes	Yes
Rotor weight (x scaling)	≈1.5	1.0	1.0	≈2.0
Pitch fan system (x scaling)	N.A.	N.A.	1.0	N.A.
Transmission per ART (.78 x V22)	1.0	1.0	1.0	1.0
ADVANCED TECHNOLOGY EXCURSIONS:		(Modify baseline values by)		
C1 (Category 1) affects all concepts				
Engine SFC	x .8	.8	.8	.8
Engine weight	x .8	.8	.8	.8
Wing drag divergence Mach no. delay	+ .05	.05	.05	.05
Additional transmission gains	x .8	.8	.8	.8
- Concept-Specific -				
C2 Propeller Compressibility				
Delay drag divergence Mach no.	+N.A.	.05	.05	.05
C3 Nacelle Drag				
Assume engine size reduced	xN.A.	.5	.5	.5
Optimize folded blade drag	x .5	N.A.	N.A.	N.A.
C4 Wing Weight				
Remove wing stiffness weight basis (e.g., control laws, etc.)	xN.A.	0	0	0
C5 Variable Geometry Weight				
Tiltfold System	x .5	N.A.	N.A.	N.A.
Variable Diameter System	xN.A.	N.A.	N.A.	.5
Tiltwing Pitch Fan	xN.A.	N.A.	.5	N.A.

by the tiltfold since the rotors are folded above about 220 knots which alleviates the proprotor stability constraint. When the blades are folded, the pod center of gravity is forward of the wing torsion axis which minimizes susceptibility of the wing to flutter in the operating range. Control system algorithms are the basis for this category.

The fifth category applies to each of the variable geometry concepts for reasons peculiar to each concept. For these, the assumption is that "50% improvements" are made in the following elements:

Tiltfold: Folded blade drag and fold system weight

Tiltwing: Yaw/pitch fan system weight (no baseline drag assumed)

VDTR: Rotor retraction system weight

Each of the above five categories is applied at 450 knots as appropriate to the aircraft type, in cumulative fashion to the baseline (current technology). The results are shown in figure A-22. For each aircraft type the first bar is baseline; the second, baseline *and* category 1; the third, baseline *and* category 1 *and* category 2; etc.

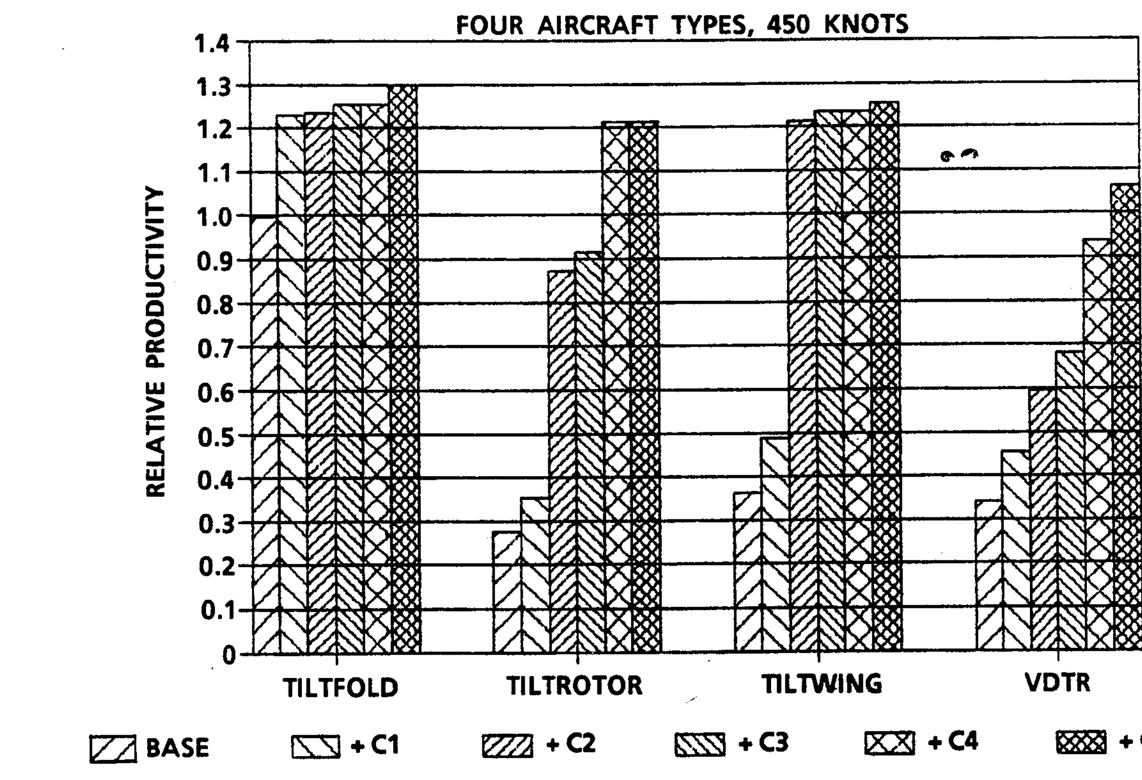


Figure A-22. Technology effects on relative productivity.

If the technology improvements can occur and can be cascaded as shown, then the propeller types come into contention with the tiltfold at 450 knots. The tiltrotor and tiltwing become about 20% better than the current technology tiltfold. The tiltfold also improves beyond baseline, principally due to general propulsion technology advances plus some improvements in tiltfold technology. The tiltfold remains as the solution with the highest productivity index at 450 knots and higher speeds.

The sensitivity of the propeller types to assumed gains in propeller technology can be illustrated with the tiltrotor over the speed range from 350 to 500 knots. The trend in this case will be illustrated by solution gross weights for the 30-passenger, 600-n.mi. mission. The purpose here is to show the effect that the speed specification has in growing gross weight and the technology assumptions needed to offset that growth. Three conditions are examined: baseline (current) technology, specific technology for the tiltrotor, and specific plus general technology. The results are shown as gross weight versus design cruise speed for the three technology levels in figure A-23. With current technology, no solution can be found for 450 knots below 100,000 lb. Specific improvements make a large change with a gross weight between 50- and 60,000 lb. The additional benefits from engine, transmission, and wing airfoil technology reduce weight at 450 knots to between 40- and 50,000 lb. At 450 knots, gross weight is most sensitive to propeller efficiency with wing stiffness alleviation being the next area. The tiltwing trends are similar (from fig. A-22) but with little penalty on wing weight due to stiffness requirements. The sensitivity to propeller efficiency indicates significant risk in setting design gross weight at 450 knots to meet a mission specification.

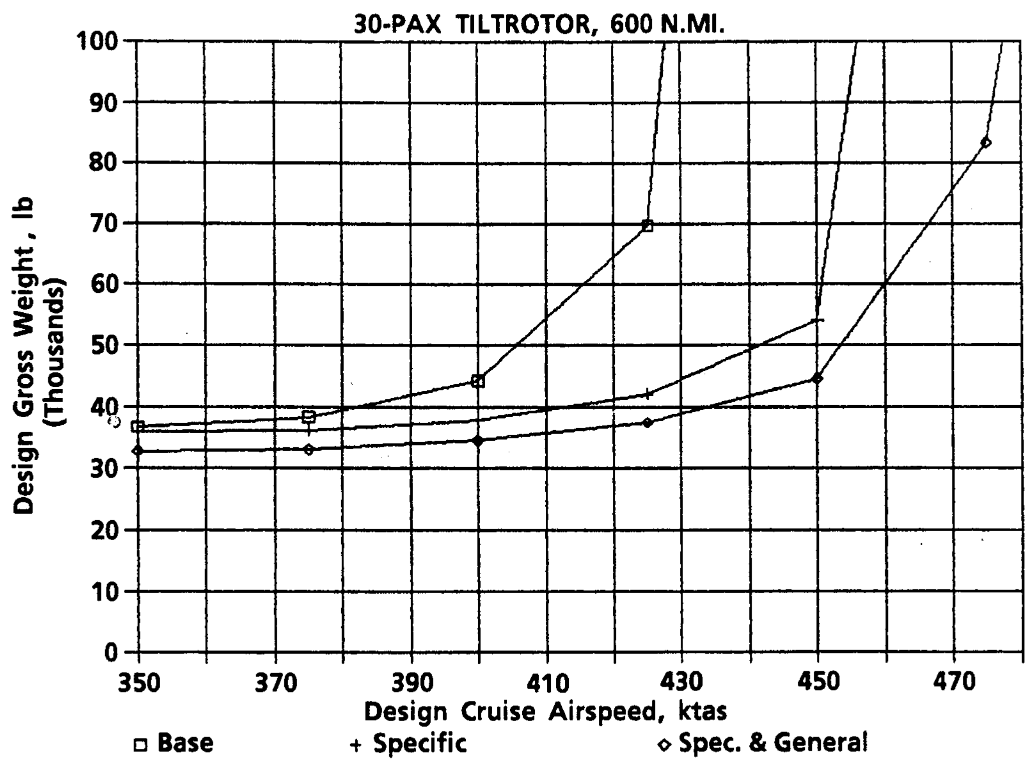


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Figure A-23. Technology effects on gross weight vs. speed.

Evaluation of Concepts Selected for Task 1

The technology excursions presented in the last section are principally indications of sensitivity independent of when the technology can be realized. This section is aimed at a preliminary assessment of integrating the technologies in a predesign for a technology demonstrator starting around year 2000. In this case, some potential gains are likely to be found to be mutually exclusive or counterproductive. For example, propeller airfoil advancements for high flight speeds that improve propeller efficiency may aggravate aeroelastic excitations or reduce damping thereby trading structural weight for engine or fuel weight. IHPTET efficiency goals may be achieved but with the airframe requiring offsetting installation requirements resulting from higher cycle temperature.

Assessments were made of an aggregated set of technology parameters resulting in the following technology increment:

Category 1 General Technology. All items in this area were taken at .9 x "current." For example, SFC for turboshaft engines that are approaching PFRT in year 2004 would be .36 at rated power rather than .4. The SFC for the convertible engine shaft power extraction at rated power would be .432 instead of .48. Transmission weights would be 70% V-22 levels rather than 78%.

Category 2 Propeller Efficiency. The delay in drag divergence Mach number effects relative to the current technology maps used was .03 instead of the .05 used in the sensitivity sweeps.

Category 3 Nacelle Drag. Left at 50%.

Category 4 Wing Stiffness Increment Weight. Left at 0%.

Category 5 Variable Geometry Weight. Left at 50%.

The above assumptions were combined and used for new synthesis runs which improved the propeller types relative to the tiltfold but not as fully as shown in the sensitivity sweeps. The results are shown in figure A-24 as productivity index for current and advanced technology for each type at 450 knots. Again, it should be noted that the low index values correspond to point designs with high gross weights. The index values below around 25 are essentially non-solutions. The sensitivity of productivity of the propeller types to small changes in prop compressibility effects means that picking the design gross weight and drawing that first centerline for these types is risky.

The tiltfold shows a significant margin. It has the potential for growing to still higher speeds where the propeller types would again vanish as contenders.

QUALITATIVE ASSESSMENTS

Merits and Problems of Each Type

The tiltrotor- The Task 1 investigation has shown that with current technology the tiltrotor produces the highest productivity of all types in the 350- to 500-knot speed range.

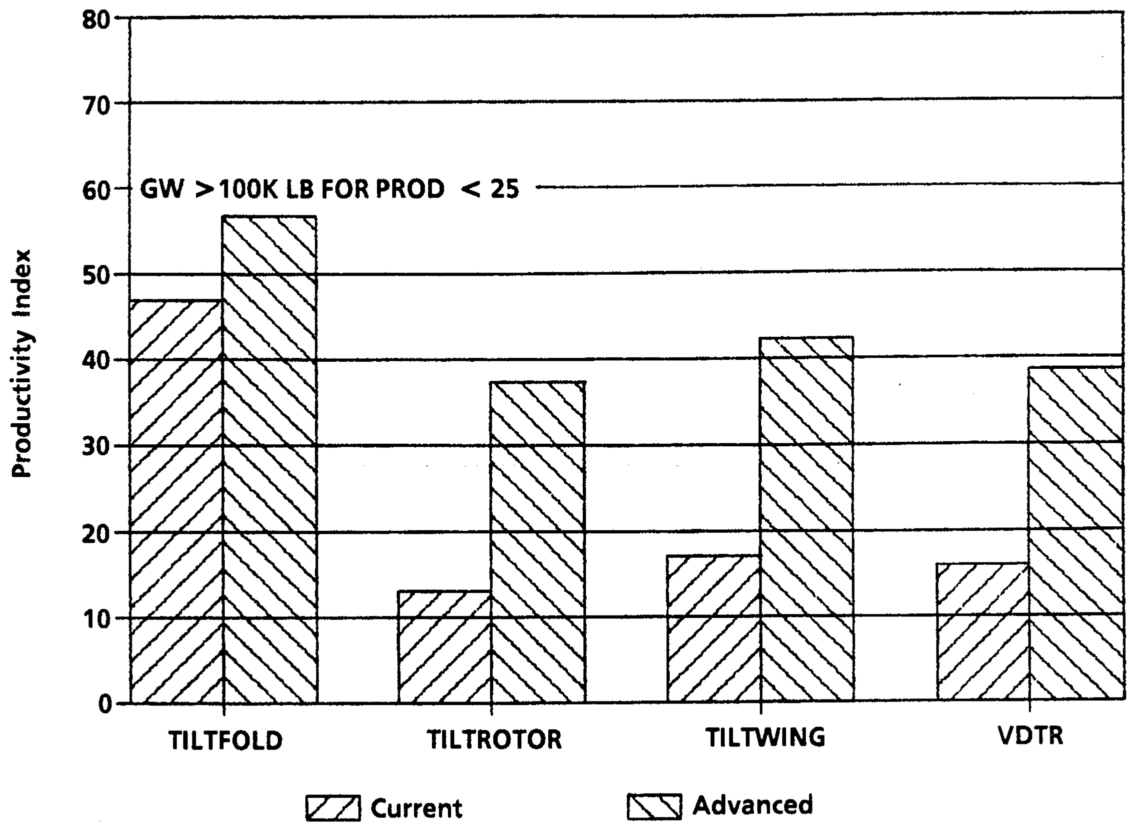

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Figure A-24. Current and advanced technology, 450 knots, 4 types.

Its speed for peak productivity occurs around 375 knots in the 30-passenger size and between 350 and 375 knots in the 15-passenger size.

However, at the speed specified for the missions of interest, 450 knots, and with current technology, gross weight solutions for firm mission payload-range specifications are very risky, if not impossible. For example, turboshaft engine size for twin engined 30-passenger aircraft go beyond 20,000 hp each.

By making aggressive assumptions for technology improvements that would benefit any propeller-driven aircraft (drag divergence delay of .03 Mach number) and additional assumptions for wing-pylon aeroelastic stability that might be applied to any wing-mounted propeller aircraft (structural and control law advances), the tiltrotor would enter the arena of 450-knot cruise speeds.

Achieving these solutions, however, requires propeller-rotor design approaches that are unique to proprotor aircraft. For example, high-speed multibladed propfans designed for Mach .8 cruise depend upon spinners that are 20 to 30% of the prop diameter to provide room for required strength, pitch change blade clearance and to avoid blade root aerodynamic thickness problems that would degrade their speed potential. For rotor diameters of around 40 feet, such a spinner diameter ratio would approximate the fuselage diameter.

The "propfan" design approach for proprotors is not a likely one because the structural loads, aeroelastic, and pitch control constraints must be satisfied on proprotors over a wide range of flight speed and skewed inflow angles from high speed propulsion to maneuvering with hover lift. These requirements have been met best with three-bladed rotors with careful attention given to blade root structural and aerodynamic thickness with spinner diameters less than 10% of the rotor diameter. To better match the proprotor thrust loading in cruise to that in hover, the engine rpm is reduced within the governor range to approximately 80%. At high cruise speeds with high helical tip Mach numbers it is best to have lower thrust loadings than encountered during hover. The data presented in references A-1 and A-2 vary this rpm ratio and the best values are in this range. Even so, the tiltrotor does not promise the best productivity for 450 knots. But the technology tasks toward this goal would certainly yield improvements at the lower speeds where the tiltrotor productivity is superior to all other concepts.

The variable diameter tiltrotor- The benefits of varying the diameter of the proprotor between hover and cruise is that the size can be tailored to the flight condition and in cruise the engine is operated up to its full rpm range. In high speed cruise, this permits a given engine to generate about 5% more power than if it's operated at 80% rpm. When cruise power requirements dictate engine size, transmission torques can then be lower by 15% than if designed for 80% rpm. If the outer portion of the blade telescopes over the inner portion, then the inner part of the rotor disk produces little significant downwash in hover and therefore downloads on nontilting engine nacelles would be avoided. In cruise, the reduction in blade area and diameter has a favorable effect on aeroelastic stability boundaries.

However, the full-rpm centrifugal loads on the blades require careful design of the inflight blade retraction system especially when large portions of the gross weight can be carried by the rotor during conversion. This leads to additional weight of the rotor and control system which in cruise mode must be considered in wing-rotor-pylon aeroelastic stability analyses. Since rpm is not reduced in cruise, some of the gains in aeroelastic speed boundaries due to rotor diameter reduction are offset by the destabilizing effects of higher rpm. The gains in propulsive efficiency relative to the fixed diameter tiltrotor have not been found to be sufficiently significant to offset the additional weights estimated for the system in the speed range below 425 knots. The productivity index may cross over and become superior to that of the tiltrotor above 425 knots with current technology, but neither would be viable. With advanced technology, the assumption is that retraction system weights are cut in half. At 450 knots, the VDTR would project to be slightly more productive than the tiltrotor. It would still not be the best at 450 knots.

The tiltwing- The merits of the tiltwing have resulted in at least two well-known test aircraft, the CL-84 and the XC-142. Even though disk loadings were higher than those generally associated with "rotorcraft," simulated hoist rescues have been demonstrated so this level of disk loading represents about the maximum considered in this study. The fact that the tiltwing minimizes downwash impingement on its wing in hover by presenting its leading edge to the propwash partially offsets the reduction in hover efficiency resulting from its higher disk loading. Further, yaw control and some pitch control in hover can be provided by deflecting the flaperons in the propwake thereby reducing the need for cyclic pitch control of the blades. The propeller thrust line in hover can be located closer to the wing root than in the other types analyzed thereby reducing jump takeoff bending moments. Also, the tilted wing presents a structural box having its larger dimension in the direction of the load. These effects are accommodated in the math model used to synthesize the designs (see table A-3). In the cruise mode, propeller efficiencies can be expected to be slightly better than the other propeller types; sufficiently so that it becomes the superior configuration as speeds reach approximately 400 knots.

However, over 425 knots propeller compressibility and advance ratio effects set in and productivity for the operator becomes insignificant. Examination of the math model results indicated that the wing weights were not needing the stiffness increments due to criteria set up for proprotor stability. More detailed design of this alternative would have to consider the effects of whirl flutter. These may be induced by the more rigid tiltwing propeller concepts at high helical tip Mach numbers on wings that have not been beefed-up for proprotor stability stiffness effects. At 400 knots, a distinct trend was noted for gross weights to reduce as disk loadings are reduced to 40 psf. (From this standpoint the tiltwing was trying to become a tiltrotor.) However, to preserve control and avoid wing stall in partial power approach and descents, it is necessary to relate wing loading and disk loading. Because the highest wing loading analyzed, 120 psf, generally produced the lowest weights and highest productivities, and because cruise rather than hover sets engine power, the disk loading for the transport aircraft was held at 60 psf. The fact that during flight operations with the wings tilted up leads to highly asymmetrical flows over the props and wing indicates that vibratory loads will be induced. In the lower disk loading concepts, these are accommodated by combinations of cyclic pitch, hub stiffness control, and blade strength. The elimination of cyclic pitch in the tiltwing means that more sophisticated solutions (and weight) are required in the propeller and support gearbox design to avoid, if possible, oscillatory loads that impair system life. Given that advanced technology levels bring productivity for the operator up into contention at 450 knots, the productivity index for the tiltwing is second best (see fig. A-24).

The tiltfold- The principal reason for the emergence of the tiltfold concept is the stated need to attain speeds as a high-speed rotorcraft that are beyond the speeds where propellers work best. At 430 knots and beyond, the weight of additional systems required by the tiltfold concept are offset by savings in fuel resulting in lower gross weight solutions. At these speeds, the fan-supercharged convertible engines are able to produce cruise thrusts with lower fuel flows than turboshaft systems which are also designed for hover. The fact that it is the sum of weight empty *and* fuel load that must be spent to do the operator's job gets obscured in measures that ignore cruise efficiency. This can happen easily when any cruise speed is accepted as a fallout from engine power based on hover requirements that are set by an all-engines-operative criteria, and when utilization is sufficiently low to deemphasize fuel investments for the system life cycle (or better, near-year perspective). When time and fuel and vertical operation are important, the high speed rotorcraft is clearly indicated. Given that combination, the tiltfold promises the highest productivity for the operator. In military configuration, it provides inherent steps toward reducing radar observables and ample space for simple, fan-augmented, infrared suppression systems. All steps in the stop-fold process were demonstrated in the only large-scale wind tunnel test of the tiltfold rotor. In February 1972, the stop-fold system was tested to speeds up to maximum for the 40- x 80-ft wind tunnel. The stop-fold process was performed at angles of attack representing moderate 1.5g maneuvers (pitch rates not included). The additional modes of flight possible with the tiltfold concept also provide mission reliability and survivability as a byproduct.

However, the cross-shaft can be a flight critical item in hover – as with the CH-46 and CH-47 helicopters. The tiltfold as analyzed in Task 1 has the engines mounted in the fuselage in order to minimize drag of the rotor pods. This leads to the importance of the cross-shaft for hover. For military missions, survivability considerations may require special treatment of this system. In cruise mode, which represents the main block of mission time, the shaft is not flight critical even in proprotor mode in that propulsion can be transferred to fans and a conventional takeoff/landing (CTOL) made at an alternate field. The tiltfold conversion process is an extension of that for the tiltrotor and as such will take several additional seconds to complete. In military missions, this process would need to be completed during maneuvers. Stop-fold conversion time is limited principally by accelerations/decelerations of the aircraft as the rotor is stopped or started entirely without the application of shaft torque. These times can be minimized in military aircraft.

Technical Issues and Key Factors

Only two issues are needed to summarize results of the Task 1 effort. For each issue the key factors are listed.

1. Given that achieving productive 450-knot cruise speed solutions with advanced propeller technology is risky, is it worth doing at all?

   The answer is yes, but as second priority to the tiltfold activity. Key factors are:

   a. Optimize high-speed airfoil, spinner, twist, planform, structures and weight for a range of cruise speeds from 350 to 450 knots, and for HOGE OEI.

   b. Optimize wing structure and control law algorithms for blade loads, and handling qualities to V_{dive} (of V_{cr} knots x 1.1 x 1.2) and for proprotor aeroelastic stability to V_{dive} x 1.15.

2. Given that the tiltfold is promising the greatest productivity at 450 knots for the operator even with current technology, how can it be considered current when the key components aren't on the shelf?

   The answer is in the definition of the program that flows from a "current" start. If time is planned within the program to design, fabricate, and test key components, then these components will be available for subsequent system integration based on a predesign of a technology demonstrator system that could start "this year." A mission payload-range specification would be derived rather than specified in order to provide a converged design using, where necessary, off-the-shelf hardware. Key factors are:

a. Validate the fan torque converter lock-up clutch described under NASA Lewis contracts that removes the necessity for variable fan geometry, guide vanes, or exit vanes. This is a key element in the "best" convertible engine system.

b. Build upon the tiltfold rotor experience with the Bell Model 627 foldrotor tested at Ames in 1972 and go the next step in providing the wide-range collective necessary to run from autorotative pitch settings in helicopter mode to the feathered settings demonstrated in the 1972 tests.

c. Conduct system engineering type tradeoffs of mission requirements and reconcile the sizing of the above components, loads, and power requirements around a single aircraft design point.

The above presumes that decisions are made to concentrate R&D tasks on productivity goals "soon;" that a concept is selected for the 450-knot cruise speed range and resources are applied to two categories: the general area like IHPTET and ART ("safe" because they benefit many programs) and the concept-specific area (because it promises the real gain in productivity). The concept-specific area contains the priority tiltfold tasks with the propeller work as second priority aimed at improving productivity in the lower speed ranges.

Mission Drivers and Other Missions

The operator will benefit from the approach described in the previous section by having a growth path from the current tiltrotor systems to a compatible system that progresses into the inevitable higher speed range. It has been shown how speed is a driver of major significance. The size of the payload has a secondary bearing on the size of the aircraft in comparison. The size of the payload may progress upward in keeping with the development of demand. The hover endurance for the high-speed rotorcraft has not been the subject of separate variations in Task 1 since the mission was basically a range mission. Although hover is possible on one engine at contingency power and cruise requires the full continuous power output of both engines, the power lapse rate for altitude cruise means that there should not be much difference expected in fuel flows between the two conditions for the rotorcraft investigated. It's the time in each mode that counts. The tiltwing will be penalized more by increases in hover time due to its higher disk loading.

Range is an important parameter. However, the fact that the NASA-defined mission is 600 n.mi. between point A and point B should not be construed as an excessive specification. Recent commercial V/STOL transport studies have been based on a more likely demand for shorter routes on scheduled operations. The fuel loads are probably equivalent because this study has a relatively simple profile with 10% reserves whereas scheduled operations even on shorter routes will require longer reserve endurances, alternate landing destinations, air traffic delay fuel allowances, etc. (These allowances should be reviewed for high-speed rotorcraft in subsequent studies because more landing areas should be available to aircraft capable of small field operation.) The specification applied to the 15-passenger size operating as a business aircraft is probably right on for sizing purposes.

The tiltfold concept opens up many new applications for multiple mode operations. Vertical operations can be initiated from a small base. Overload takeoffs can be made from short runways in the STOL mode or from long concrete in the CTOL mode. Landings can be made vertically, short, or long depending on circumstances. The sketch in figure A-25 summarizes some of the operational mission flexibilities that can be expected with the tiltfold concept.

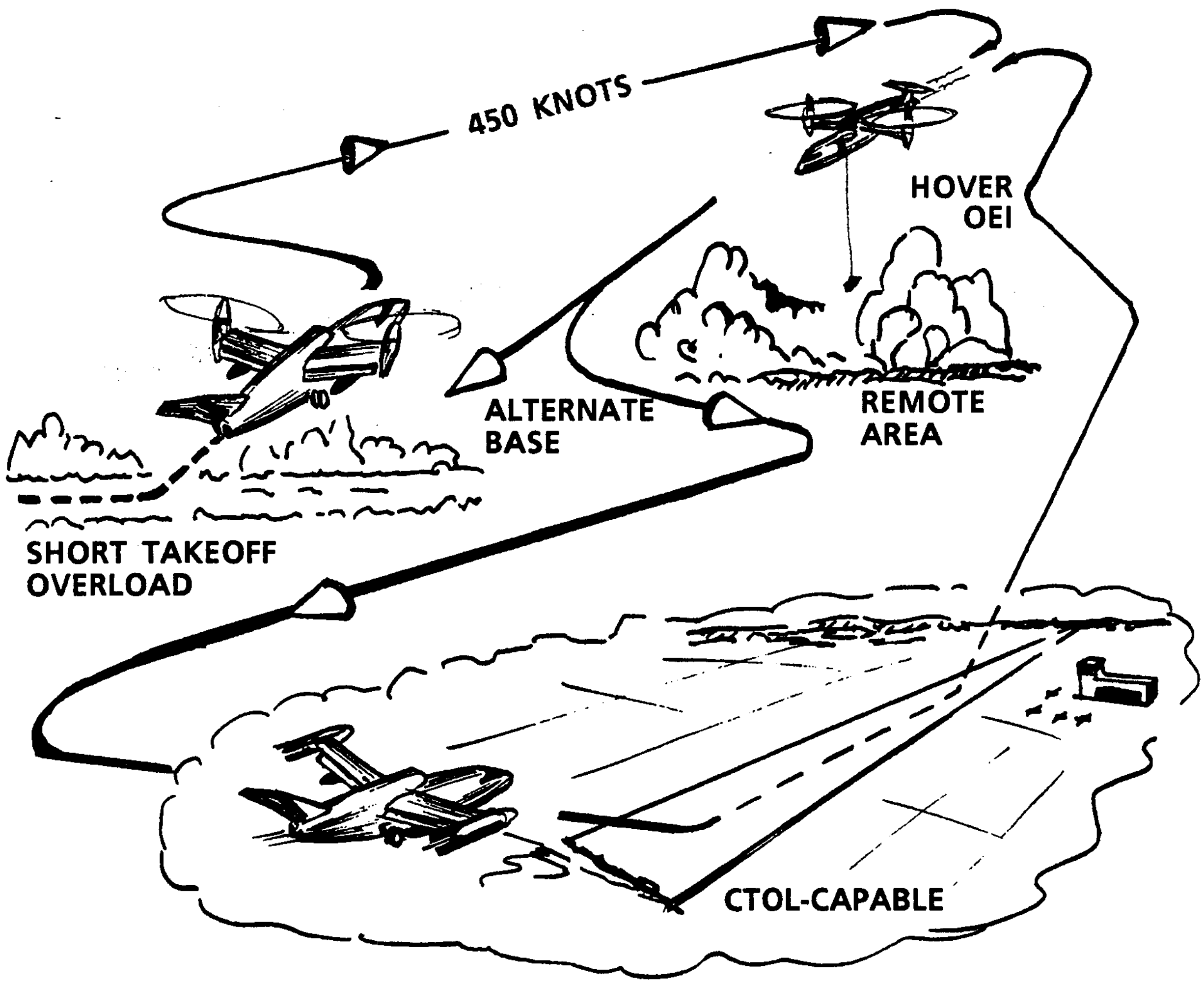

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Figure A-25. Mission flexibility with the tiltfold aircraft.

RECOMMENDATIONS

The recommendations for Task 2 based on the results described in the previous sections and on the requirement for using current technology for the analysis of Task 2 configurations are as follows:

1. For the two concept-mission configurations at 450 knots, the only concept leading to mathematically converged designs at that speed, the tiltfold, is selected and applied to two mission sizes: the 15- and the 30-passenger aircraft. The 15-passenger aircraft will have three-abreast seating and the 30-passenger will have four-abreast seating.

2. To provide a second concept configuration, the tiltrotor configuration in the 30-passenger size will be reviewed at the maximum productivity speed of 375 knots and discussed from the standpoint of technology tasks that can lead to:

   a. improved speeds for peak productivity, or

   b. improved productivity at the baseline peak-productivity speed.

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13. ABSTRACT *(Maximum 200 words)*

The spectrum of VTOL type aircraft is examined to determine which aircraft are most likely to achieve high subsonic cruise speeds and have hover qualities similar to a helicopter. Two civil mission profiles are considered: a 600-n.mi. mission for a 15- and a 30-passenger payload. Applying current technology, only the 15- and 30-passenger tiltfold aircraft are capable of attaining the 450-knot design goal. The two tiltfold aircraft at 450 knots and a 30-passenger tiltrotor at 375 knots were further developed for the Task II technology analysis. A program called HI-STEP is recommended to meet several of these issues based on the tiltrotor concept. A program called TFS is recommended based on the tiltfold concept. A task is identified to resolve the best design speed from productivity and demand considerations based on the technology that emerges from the recommended programs. HI-STEP's goals are to investigate propulsive efficiency, maneuver loads, and aeroelastic stability. Programs currently in progress that may meet the other technology needs include IHPTET (NASA Lewis) and the Advanced Structural Concepts Program funded through NASA Langley.

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